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Petrology and geochemistry of the Ringing Rocks pluton Jefferson County Montana

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PETROLOGY AND GEOCHEMISTRY OF THE RINGING ROCKS PLUTON, JEFFERSON COUNTY, MONTANA

by

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ABSTRACT

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Petrology and Geochemistry of the Ringing Rocks Pluton, Jefferson County, Montana.

Ringing Rocks pluton is a small composite intrusion on the southeastern periphery of the Boulder batholith, Montana. The pluton consists of a quartz-bearing monzonite core partly surrounded by a conformable rim of mafic monzonite. Near contemporaneous emplacement of the two intrusions is supported by field relations and by the presence of an intervening zone of mixing. The transitional zone displays a chemical composition that is intermediate between the core and mafic rim. The core of the pluton is chemically compatible with the calc-alkaline suite of the Boulder batholith, whereas the mafic-monzonite rim is chemically and mineralogically similar to rocks of the shoshonite association. Shoshonites are potassium-rich, silica-saturated rocks that exhibit chemical affinities for both the calc-alkaline and alkaline rock associations. In addition to the mafic-monzonite rim of Ringing Rocks pluton, potassium-rich alkaline rocks occur along the northern-most contact of the Boulder batholith. These occurrences suggest that alkaline magmatism in Montana can be extended somewhat in both space and time to include the shoshonite and alkaline rock types associated with the Boulder batholith of western Montana.

Director: D.W. Hyndman

D. Hall for D.W. Hyndman

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CHAPTER I

INTRODUCTION

General Statement

Ringing Rocks pluton is a small composite intrusion consisting of a central body of quartz-bearing monzonite partly enclosed in a conformable rim of mafic monzonite. Interaction between the two magmas produced a narrow zone of intermediate composition that grades imperceptibly into the quartz-bearing monzonite core. Quartz-bearing monzonite in immediate contact with surrounding volcanic country-rock on the east side of the pluton does not show evidence of contamination. Field relationships, linear chemical-trends, and petrographic evidence strongly support a magma-mixing model for the hybrid transitional zone.

Although Ringing Rocks pluton is contemporaneous with, and situated near, the Boulder batholith, its petrogenic affinity is not obvious. Early mafic-rocks associated with the batholith are volumetrically small, constituting less than 1% of the exposed batholith. They occur primarily as dikes, ring dikes, and small plugs of assorted mineral compositions (Smedes, 1966). Detailed investigations of these rocks are notably scarce in the literature, but most appear to be compositionally akin to the mafic rim of Ringing Rocks pluton.

A characteristic feature of the mafic rim is its chemical composition, which is comparable to rocks of the shoshonite association. Shoshonites are mildly potassic, near silica-saturated rocks that exhibit

chemical affinities for both the alkaline and calc-alkaline rock-associations (Morrison, 1980). They commonly occur with rocks of the calc-alkaline suite, and are the dominant rock-type in parts of the central Montana alkalic province (Woods, 1976).

The Butte Quartz Monzonite is the largest, single pluton and dominant rock-type of the Boulder batholith. It is fairly homogeneous in composition but exhibits local variations in texture (Becraft, et al., 1963). A porphyritic variety containing potassium-feldspar megacrysts up to 3 centimeters in length occurs approximately ½ kilometer west of the Ringing Rocks pluton (Prostka, 1966). The quartz-bearing monzonite of the pluton's core, however, is roughly equigranular, with all major minerals rarely exceeding 2 millimeters in length. Moreover, the core does not contain hornblende, a major mafic-component of the Butte Quartz Monzonite. The dominant amphibole is pale-green actinolite with common cores of relict pyroxene.

The purpose of this chemical and petrographic investigation is threefold: to describe the pluton's mineralogical and textural relationships, determine its association with the Boulder batholith, and provide a reasonable model for its origin. The unique juxtaposition of rock types in the Ringing Rocks pluton is enhanced by the small size of the pluton, less than 900 meters in diameter. Any rational petrogenic interpretation must take into account that complex relationships are occurring in a very restricted regime. Furthermore, the alkaline character of the mafic rim precludes scenarios based solely on the evolutionary history of the Boulder batholith. Petrogenic implications must extend beyond the pluton's immediate confines to areas where rocks exhibit compatible chemical

affinities.

Location

Ringing Rocks pluton is approximately 25 kilometers southeast of Butte in T2N, R5W, sections 4 and 9, Jefferson County, Montana (Figure 1). It is accessible from Interstate 90 by turning north at the Pipestone exit. The unimproved dirt-road crosses near-horizontal, basin-fill sediments and abruptly climbs to the base of the pluton. A four-wheel drive vehicle is advisable as portions of the road are deeply scoured by intermittent drainage-channels.

Trees and brush are sparse, and exposure is excellent. The highest elevation of the pluton is in the quartz-bearing monzonite core at 1820 meters. Maximum relief between the core and mafic-monzonite rim is 160 meters.

Previous Work

The pluton was originally mapped by Prostka (1966) as part of a geological survey of the Dry Mountain 7½ minute quadrangle. Although the study focuses on the area's volcanic rocks, Prostka does provide a brief description of the pluton's core and mafic rim. The transitional zone was not recognized.

Most of the mafic rocks associated with the batholith are not well exposed, making the Ringing Rocks' rim a prized target for investigative studies. Several articles on the Boulder batholith refer to the mafic rim in discussing the batholith's earliest plutonic activity (Tilling, 1973, 1974). K-Ar age determinations on the rim's biotite were performed

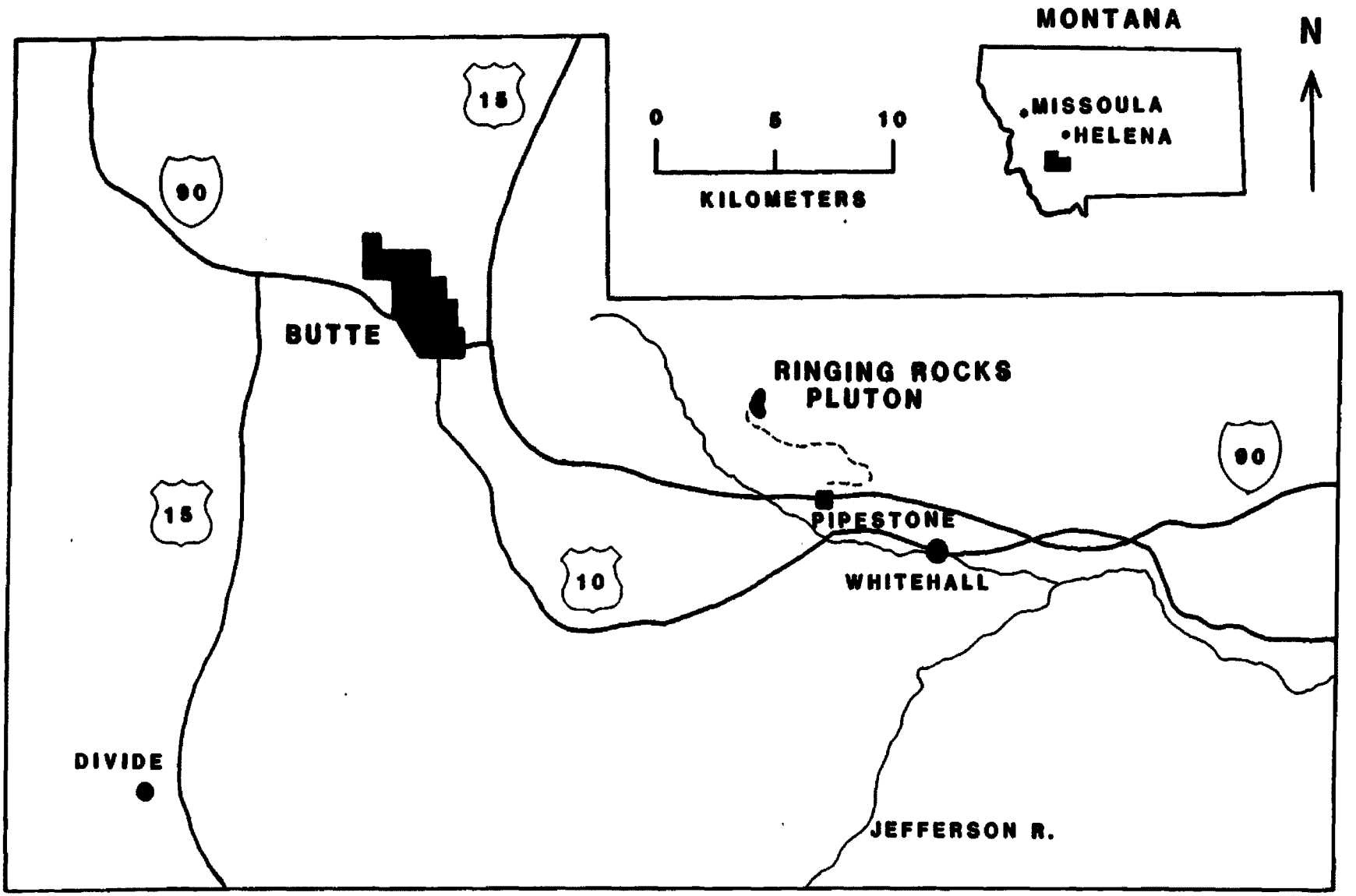


FIGURE 1. INDEX MAP OF WESTERN MONTANA SHOWING LOCATION OF RINGING ROCKS PLUTON.

by Obradovich (Tilling, et al., 1968) and later by Berg and McClernan (in Daniel, et al., 1981, p. 72). The rim is also a mafic representative in studies on the batholith's thorium and uranium contents (Tilling, et al., 1969).

CHAPTER II

GENERAL GEOLOGY

Regional Setting

Ringing Rocks pluton is on the eastern periphery of the late-Cretaceous Boulder batholith of southwest Montana (Figure 2). The batholith is a composite mass 100 kilometers long and 50 kilometers wide consisting of successive intrusions of varying composition. Rock types range from syenogabbro to alaskite, but quartz-bearing monzonite and granodiorite predominate (Tilling, 1974). Radiometric age-dates and field relations indicate that plutons of the batholith were emplaced within a 10 million year interval 78-68 million years ago (Tilling, et al., 1968).

The largest, individual pluton, the Butte Quartz Monzonite, is centrally located and constitutes more than 70% of the exposed batholith. More than a dozen smaller plutons make up the remaining 30%. The batholith intrudes early Precambrian regionally-metamorphosed rocks; late Proterozoic (Belt), Paleozoic, and Mesozoic sedimentary strata; and late Cretaceous, cogenetic volcanic-rocks. The Elkhorn Mountains Volcanics are the batholith's own volcanic ejecta preserved along the batholith's flanks, and as remnant roof-rocks within various plutons (Figure 2).

The nature of the Boulder batholith has been a subject of intense debate. Klepper and others (1971a, 1974) believe the batholith is a vertically emplaced, steeply dipping, epizonal pluton whose outline was in part controlled by pre-existing structural trends. They also maintain

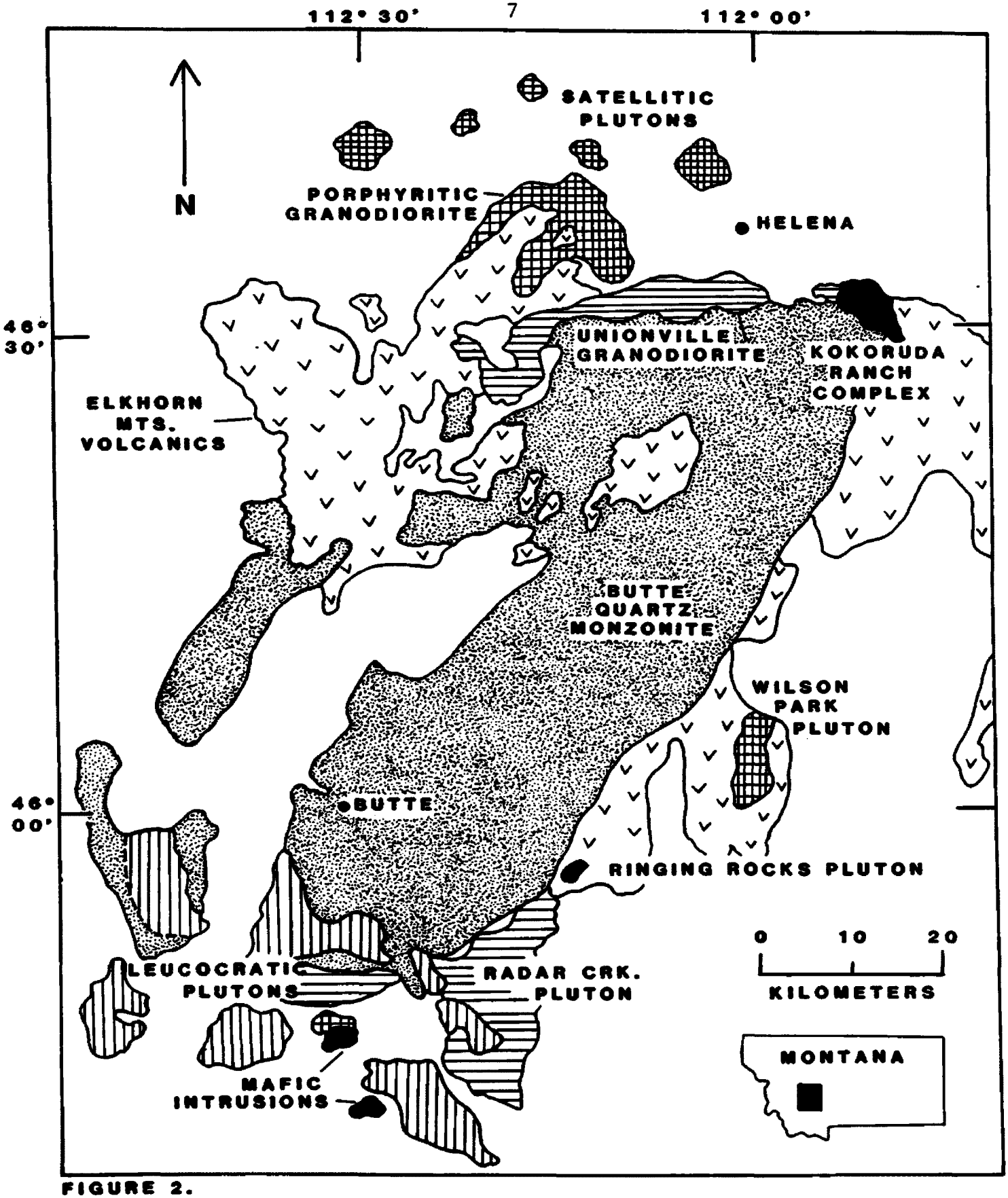


FIGURE 2.

GENERALIZED GEOLOGIC MAP OF THE BOULDER BATHOLITH, MT

(modified from Smedes, et al., in Miller, 1973, p. E-2)

that the batholith is 15 to 25 kilometers thick. Hamilton and Myers (1974), on the other hand, view the batholith as a shallow, laterally emplaced, sheet-like body whose age and composition approximates that of the associated Elkhorn Mountains Volcanics. Maximum thickness of the batholith, they contend, does not exceed 5 kilometers.

Definitive data to support either hypothesis are lacking. Compositional studies by Tilling (1973, 1974), however, indicate that several features of the batholith are not adequately explained by the Hamilton and Myers model. Tilling divides most of the batholith's plutons into two distinct geographic groups that differ chemically, isotopically, and in age. Plutons in the northern and central portions of the batholith define Tilling's main magma series and exhibit a higher potassium and lower sodium content than southern plutons of the sodic magma series. Each group's plutons are isotopically compatible, and main-series plutons are, on the average, older than plutons of the sodic series. As illustrated in Figure 2, main-series plutons include the Butte Quartz Monzonite, Unionville Granodiorite, and all mafic bodies, while the sodic series consists of the Radar Creek and leucocratic plutons. Most satellitic plutons, indicated by a checkered pattern, cannot be unequivocally assigned to either magma series.

Tilling concluded that the Boulder batholith is a composite pluton consisting of two essentially contemporaneous but distinctly separate magma-series that originated from two or more sources. In view of the batholith's limited size, Tilling believes his findings are more adaptable to a pluton that varies vertically rather than laterally. In addition, Tilling found that all stratigraphic members of the Elkhorn Mountains

Volcanics are compositionally similar to rocks of the main-series plutons. This presents a problem in the Hamilton and Myers model if volcanic rocks are compositionally different from the nearby plutons. Such a situation exists in the southeastern part of the batholith near Ringing Rocks pluton. Hamilton and Myers maintain that the area's volcanic rocks are the extrusive equivalent to granodiorites of the Radar Creek and related plutons. These plutons, however, constitute the sodic magma-series and are unrelated to the Elkhorn Mountains Volcanics (Tilling, 1974).

Regional Structure

Ringing Rocks pluton is on what some authors believe to be a major prebatholithic shear-zone (Klepper, et al., 1971a, 1974; Prostka, 1966). The fault trends north-northeast from the Radar Creek pluton, southeast of Butte, to the Kokoruda Ranch complex (Smedes, 1966), southeast of Helena. It separates the Butte Quartz Monzonite from flanking prebatholithic rocks, and is thought to be the structural element responsible for the relatively straight, and predominantly steep, eastern contact of the Boulder batholith.

Hamilton and Myers (1974) do not believe that the east margin of the batholith is a fault-controlled contact, but do concur that the contact in the vicinity of the Ringing Rocks pluton is steeply dipping and anomalously straight. They attribute this to either the continuation of a prebatholithic, isoclinal anticline that is exposed on the western contact of the Radar Creek pluton (Figure 2), or to the continuation of the pluton itself. Klepper and others (1971a, 1974), however, interpret the intervening metasediments between the Radar Creek pluton and Butte Quartz

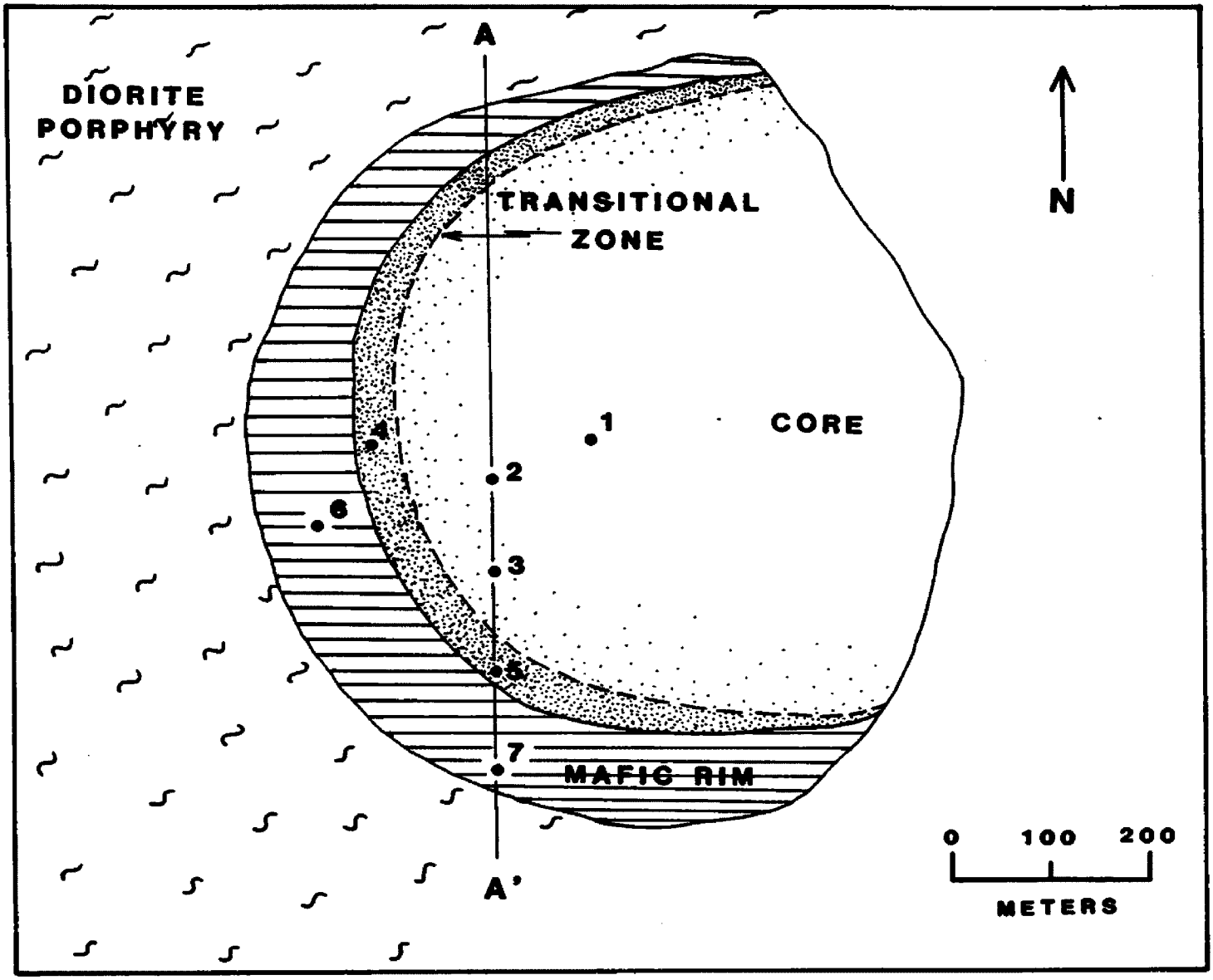
Monzonite as roof or wall rock, not upward projections of the prebatholithic floor. They also do not believe that granodiorites of the Radar Creek pluton extend beyond their present area of exposure.

In either event, Elkhorn Mountains volcanic rocks near the Ringing Rocks pluton are pervasively sheared and foliated (Prostka, 1966). Butte Quartz Monzonite rocks immediately adjacent to the contact, however, show not evidence of deformation. These relationships suggest that in this area, at least, the emplacement of the batholith's eastern margin, and possibly the Ringing Rocks pluton, was structurally controlled.

General Geology of Ringing Rocks Pluton

Ringing Rocks pluton is a composite of two magmas that form the core and rim, and intermixed to form the intervening transitional zone. In plan view, the pluton is a circular body approximately one square kilometer in area (Figure 3). The core of the pluton, a medium-grained quartz-bearing monzonite, is surrounded on the west by a crescent-shaped intrusion of mafic monzonite. Interaction between the two intrusions created an intervening quartz-bearing monzonite that is significantly more mafic than the core. This rock-type does not occur where the core is in direct contact with volcanic country-rock, thus dismissing the possibility that it is a chilled margin of the core, or formed by contamination by those country rocks.

The pluton is virtually structureless. The cross-sectional view depicted in Figure 3 is purely speculative and does not represent structural data obtained in the field. However, the steeply-dipping, vertically-emplaced relationships shown in Figure 3 follow several lines of



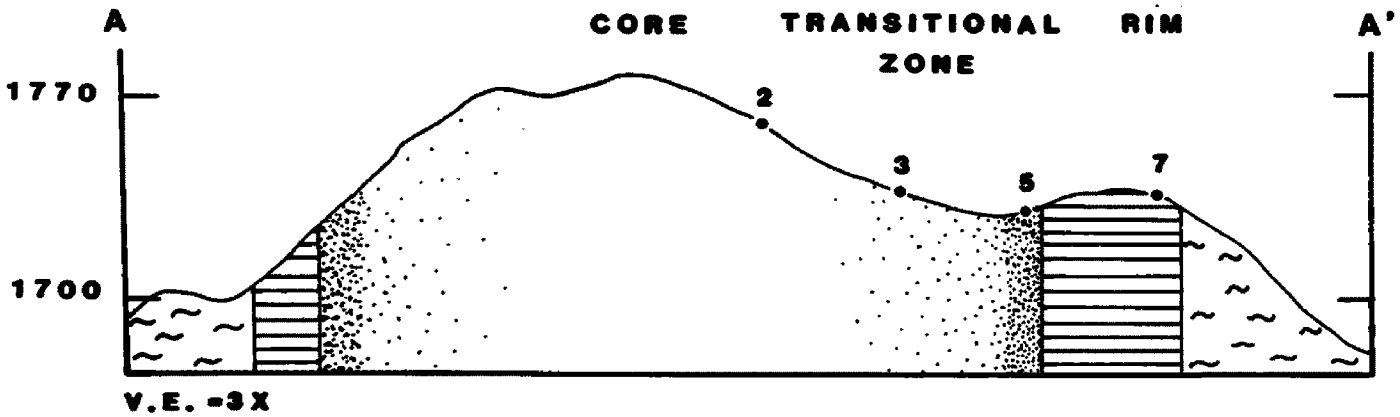


FIGURE 3. GENERAL GEOLOGIC MAP AND CROSS-SECTION OF THE RINGING ROCKS PLUTON WITH SAMPLE LOCATIONS (1-7) FOR WHOLE-ROCK CHEMICAL ANALYSES.

reasoning. First, the majority of mafic rocks associated with the Boulder batholith occur as dikes and cross-cutting plugs. Secondly, the steeply dipping, eastern contact of the neighboring Butte Quartz Monzonite suggests that the core and mafic rim of the Ringing Rocks pluton may have been similarly emplaced. Finally, much of the transitional zone is topographically lower than the mafic-monzonite rim. It does not seem likely, therefore, that the mafic monzonite constitutes the lowest stratigraphic memeber of a vertically-varying pluton. For these reasons, Ringing Rocks pluton is envisioned as a lateral composite of two, near-contemporaneous igneous-intrusions, whose vertical emplacement, conceivably, was structurally controlled.

The pluton intrudes a sheeted complex of prebatholithic diorite porphyry and Elkhorn Mountains vocanic-tuffs thermally metamorphosed to fine-grained hornfelses by the Boulder batholith. According to Prostka (1966), the recrystallized diorite-porphyry contains relict plagioclase phenocrysts in a groundmass of potassium feldspar, quartz, plagioclase and biotite. Both Prostka (1966) and Hamilton and Myers (1974) note that unmetamorphosed diorite porphyry and volcanic tuff are petrologically and texturally similar, and suggest that they came from the same magma source. Tilling (1974), however, found the porphyry lower in silica and potash and higher in calcium than the associated volcanic rocks. He concluded that the diorite porphyry is more compositionally akin to the mafic rocks of the main-series plutons.

The volcanic tuffs form the basal unit of the Elkhorn Mountains Volcanics. Biotite from unmetamorphosed tuffs in the vicinity of the Ringing Rocks pluton yielded a K-Ar age of 78 $\pm$ 1.7 m.y. (in Daniel,

et al., 1981, p. 69). Although the diorite porphyry has not been dated, Prostka (1966) believes that it intruded soon after deposition of the volcanic rocks.

K-Ar age-determinations on biotite from the pluton's mafic rim yielded an age of 78.2 ± 3.1 m.y. (Tilling, et al., 1968), and 75.1 ± 2.8 m.y. (in Daniel, et al., 1981, p. 72). The overlap of these two age-dates gives an age of between 77.9 and 75.1 m.y. for the mafic-monzonite rim. This agrees with the 79.6 - 74.3 m.y. age date obtained from similar mafic-rocks of the Kokoruda Ranch complex (Tilling, et al., 1968), and establishes them as the batholith's earliest intrusive rock-type. The pluton's central quartz-bearing monzonite body has not been dated. The gradational transitional zone and conformable, crescent-shape of the mafic rim, however, indicate that emplacement of the main plutonic-mass was essentially contemporaneous with the mafic-monzonite rim.

Field Relations

All three rock types of the Ringing Rocks pluton are well exposed. The quartz-bearing monzonite core occurs as large, rounded boulders typical of outcrop throughout the batholith. The rock is homogeneous overall with rare occurrences of spherical mafic-xenoliths, 5 to 20 centimeters in diameter, and occasional veins of micrographic granite. An abandoned mine-shaft within the quartz-bearing monzonite core exposes thin, vertical quartz-tourmaline veins with minor wall-rock alteration. Prostka (1966) notes that mineralization is negligible throughout the Dry Mountain quadrangle.

The core grades imperceptibly into the intermediate transitional

zone, becoming increasingly more mafic as the mafic-monzonite rim is approached. The contact between the transitional zone and mafic rim is not exposed, but outcrops within a meter of each other do not exhibit evidence of chilling, or of intrusion of one by the other.

The mafic-monzonite rim is best exposed on the south end of the pluton where it occurs as a small felsenmeer of subangular blocks 1 to 5 meters across. The rock is weathered to a rusty-brown and exhibits a pitted, "vesicular-looking," surface. Fresh surfaces reveal a medium-grained, dark-grey rock with shiny plates of biotite. The name of the pluton is derived from this area as the rock is extremely dense and rings melodically when struck with a hammer. Since the rock does not produce the same sound in outcrop, the bell-like quality of the blocks is probably due to their mutual suspension above ground.

CHAPTER III

ROCK DESCRIPTIONS

General Comments

Ringing Rocks pluton consists of three distinct zones whose mineralogical trends are illustrated in Figure 4. The core consists of quartz-bearing monzonite that becomes enriched in mafic components to form the transitional zone. The transitional zone contains up to 30% combined actinolite, biotite, and relict pyroxene, and is correspondingly depleted in felsic constituents. Delineating the core and transitional zone in the field is difficult because of the gradational contact between them. The distinction is obvious, however, when the two are compared together in representative hand samples, thin-section, and whole-rock chemistry.

The pluton's mafic rim has several different rock-names in the literature. I adopted Prostka's (1966) usage of "mafic monzonite" because it best conveys the rock's feldspar content and alkalic nature. Despite its dark color, the rock contains almost 60% total feldspar. Moreover, the dominant feldspar is orthoclase, clearly apparent in thin-section and in the rock's high potassium-content. The rim is compositionally distinct from the core and transitional zone, but generally compatible with the pluton as a whole. This is best expressed in chemical variation diagrams, which reveal strong linear trends from the rim inward. Mineralogical similarities, although not as obvious, do exist, and further support the intimate chemical relationship exhibited among the pluton's three zones.

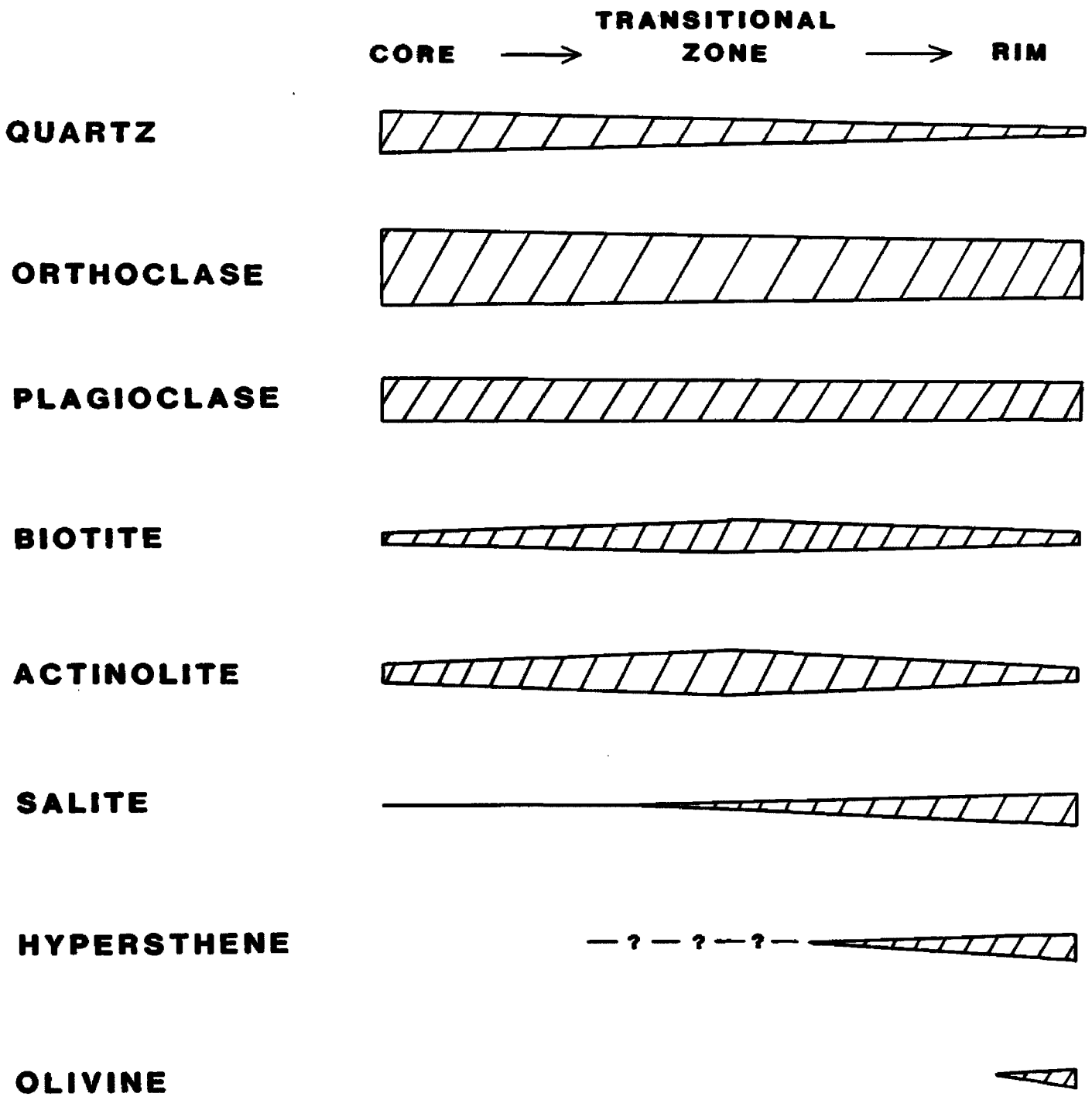


FIGURE 4. MODAL MINERALOGY CHANGES FOR RINGING ROCKS PLUTON

Quartz-Bearing Monzonite Core

The core is a pinkish-grey, medium-grained, structureless rock containing 40-45% orthoclase microperthite, 20-25% normally zoned plagioclase (An_{55-20}), 15-20% anhedral quartz, 7-10% pale-green actinolite, 6-8% brown biotite, 1-2% relict pyroxene in actinolite cores, and minor sphene, apatite, chlorite, magnetite, and zircon. The rock is homogeneous and displays a granitic texture in hand sample.

Thin-sections reveal a roughly equigranular texture with all major minerals randomly oriented and averaging 1.5 mm in length. Table 1 summarizes the principal petrographic features of the rock's major minerals. Distinguishing textural-mineralogical characteristics of the core are its lack of potassium-feldspar megacrysts and hornblende, and its relative abundance of actinolitic pseudomorphs.

Potassium-feldspar megacrysts are common in the younger, more-felsic plutons of the batholith, and are virtually absent in older, granodioritic intrusions (Doe, et al., 1968). Outcrops of porphyritic Butte Quartz Monzonite, containing potassium-feldspar megacrysts up to 3 cm in length, occur within 650 meters of Ringing Rocks pluton (Prostka, 1966). The core, however, contains fine- to medium-grained (0.5-3.0 mm), anhedral to subhedral laths of microperthitic orthoclase.

Mafic minerals consist of approximately 15% combined actinolite, biotite and relict pyroxene. The rock's amphibole is a pale-green, "ratty" actinolite with common cores of relict, colorless pyroxene. The grains are internally altered to chlorite, biotite and magnetite, producing a sieve-textured appearance. They commonly occur as ragged pseudomorphs after pyroxene, and display incomplete, 8-sided outlines.

MINERAL	%	COLOR	SIZE	HABIT	OPTICAL PROPERTIES	ALTERATION PRODUCTS	DISTINGUISHING CHARACTERISTICS
ORTHOCLASE	40-45	dusty in plain light	0.5-3.0 mm avg. 1.5	subrounded, subhedral, poikilitic laths	$2V_x$ = 45-50° Carlsbad twins	pervasive kaolin dustings	rare micrographic rims microperthitic inclusions: biotite, zircon, quartz, plagioclase
PLAGIOCLASE	20-25	dusty in plain light	0.5- 3.0 mm avg. 1.5	subhedral, prismatic laths & equant grains	$An_{(55-20)}$ avg. 45 complex twinning oscillatory & normal zoning	sericite and saussurite along specific zones	severe alteration along inner zones occasional rims of albite strong normal zoning weak oscillatory zoning
QUARTZ	15-20	clear	0.5-2.5 mm avg. 1.5	anhedral, subangular grains and interstitial stringers	$2V_z$ = 0° mod. undulose extinction	none	rare myrmekitic texture in plag. rims micrographic texture in K-spar inclusions: minor biotite & plag.
ACTINOLITE	7-10	pale green	1.0-3.0 mm	subhedral, frayed & ragged pseudomorph after pyx.	$2V_x$ = 74-76° $Z\wedge c$ = 13-15° pleochroic: X= yell. green Y= pale yellow Z= blue green	biotite chlorite magnetite	8-sided psuedomorphs with relict cores of colorless pyroxene, prominent biotite & chlorite alteration, "ratty" appearance, low-mod birefringence
BIOTITE	6-8	med. brown	0.5-2.0 mm	subhedral, ragged, platy laths	$2V_x$ = 0° pleochroic: X=Y= pale yell. Z= med. brown	magnetite chlorite sphene	ragged and broken primary laths secondary alteration of actinolite inclusions: apatite & sphene
PYROXENE	1-2	colorless	0.5-1.0 mm	relict cores in actinolite	$2V_z < 60°$ oblique ext. low-mod. birefrg. 90° cleavage	actinolite	relict cores in actinolite

TABLE 1. Mineralogy of the quartz-bearing monzonite core

The amphibole's extinction and optical angles were measured on a Zeiss 4-axis universal stage. The cores of relict pyroxene are not sufficiently preserved for precise optical determinations, but do provide a $2V_z$ of less than 60^o. The amphibole gives a $Z \wedge C = 13\text{-}15^o$, and a $2V_x = 74\text{-}76^o$, corresponding to an actinolite composition (Tröger, 1979, p. 93). Similar occurrences of actinolite pseudomorphs are found in granodiorites of the Radar Creek pluton (Tilling, 1964), and quartz-bearing monzonites of the Kokoruda Ranch complex (Smedes, 1966).

Paragenesis: The paragenetic sequence of the quartz-bearing monzonite core, as inferred from textural relationships, is illustrated in Figure 5. Pyroxene, if primary, and plagioclase appear to be the first minerals to have crystallized. Both are free of inclusions, and plagioclase constitutes the larger, well-formed grains of the rock.

The pyroxene's paragenetic relationship to the core is uncertain because of the possibility that it was derived from an outside source. Pyroxene in the quartz-bearing monzonite core is not in equilibrium with the surrounding mineral assemblage, indicating that pyroxene did not originate from the environment in which it now occurs. The core may have incorporated pyroxene from the mafic-monzonite rim via mechanical mixing of the two magmas, or assimilated pyroxene xenocrysts from an unknown source-rock. Other rocks with compositions similar to that of the core and containing pyroxene are associated with the Boulder batholith. In most, if not all, cases however, pyroxene is partly resorbed and replaced by an amphibole and nowhere occurs as distinct, individual grains (Tilling, 1964; Smedes, 1966).

Unfortunately, the core's pyroxene cannot be compositionally compared

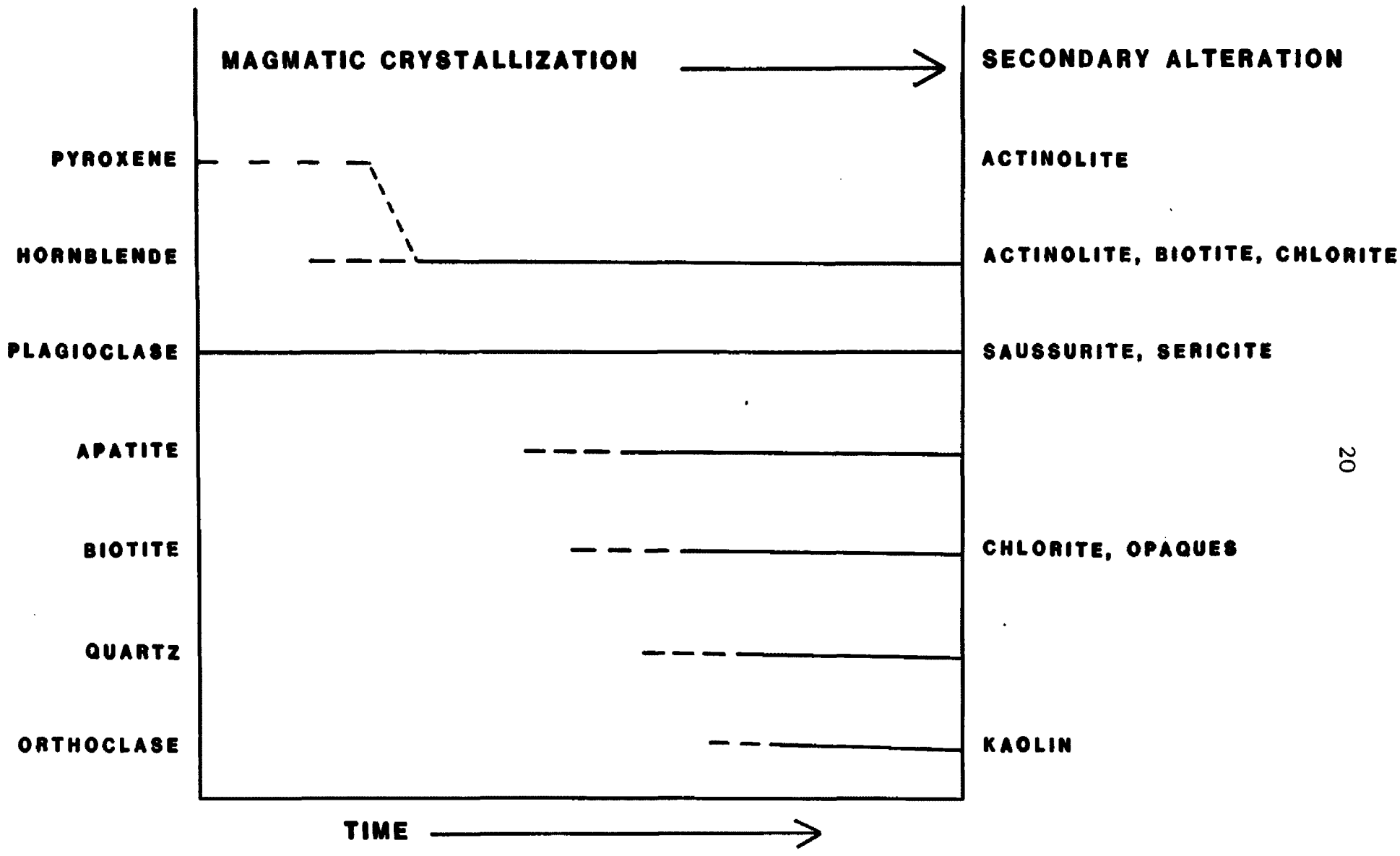


FIGURE 5. PARAGENESIS OF THE QUARTZ-BEARING MONZONITE CORE

with pyroxenes from the mafic rim because the core pyroxene is insufficiently preserved for accurate optical determinations. Whether the pyroxene crystallized directly from the magma, or was incorporated into it through magma mixing or assimilation, is not known. However, it is apparent from textural relationships that in either event, pyroxene is one of the earliest mineral-constituents of the core, and that it is no longer in equilibrium with the rock's mineral assemblage.

Actinolite, which contains minute inclusions of plagioclase, replaces the core's pyroxene and commonly retains its crystallographic outline. The amphibole also occurs as distinct, pseudohexagonal and prismatic grains that do not appear associated with any pre-existing pyroxene. Because actinolite is not stable under the P-T conditions of a crystallizing magma (Deer, et al., 1966, p. 164), these textures suggest that actinolite also replaced the rock's primary, magmatic amphibole. The composition of the quartz-bearing monzonite core indicates that its primary amphibole was probably hornblende. Hornblende, in which case, began forming after the initiation of plagioclase crystallization, and before the remaining mineral-components of the rock.

Plagioclase, quartz, and microperthitic orthoclase follow Whitney's (1975) experimental crystallization sequence for a synthetic granodiorite at P_t = 2kb and 1% H_2O. These parameters seem applicable to the pluton's core because there are no associated pegmatitic rocks to suggest water-saturated conditions, and the pluton's level of emplacement is probably correlative with the Boulder batholith's shallow emplacement of $\leq$ 2kb (Hyndman, 1981). Whitney's model shows that under such conditions, plagioclase is the first mineral to begin crystallizing, followed by quartz,

and finally, alkali feldspar. Although the core does not contain potassium-feldspar megacrysts, orthoclase does appear to be the last mineral to begin crystallizing as every other mineral occurs a minute inclusions within it.

Transitional Zone

The transitional zone is a greenish-grey, medium-grained rock containing 35-40% poikilitic microperthite, 23-26% normally-zoned plagioclase (An_{58-20}), 13-18% pale-green actinolite, 10-13% brown biotite, 7-10% anhedral and interstitial quartz, 2-4% relict pyroxene, and minor chlorite, magnetite, apatite, sphene, and zircon. It forms a narrow zone less than 50 meters in width that gradually diffuses into the more felsic core. The transitional zone is present everywhere the mafic-monzonite rim surrounds the core.

Petrographic features of the major minerals in this unit are listed in Table 2. Other than a twofold increase in mafic components, the rock is texturally similar to the core in hand sample. It does, however, exhibit several distinguishing characteristics in thin-section, principally among its felsic constituents.

Microperthitic orthoclase, which is slightly depleted in the transitional zone, averages twice the size of that in the core. The grains, 1.0-5.0 mm in length, are predominantly anhedral, rounded, optically-continuous masses that partly, or totally, surround all other major minerals. Enclosed plagioclase laths are partly resorbed. Microperthitic blebs and stringlets in the orthoclase are not as abundant as in the core, whereas micrographic intergrowths of quartz are somewhat more prevalent.

MINERAL	%	COLOR	SIZE	HABIT	OPTICAL PROPERTIES	ALTERATION PRODUCTS	DISTINGUISHING CHARACTERISTICS
ORTHOCLASE	35-40	turbid in plain light	1.0-5.0 mm avg. 3.0	anhedral, rounded, poikilitic grains	$2V_x$ = 45-47° microperthitic blebs & strngrs Carlsbad twins	pervasive kaolin dustings	poikilitically encloses plag. laths, biotite, hornblende & actinolite plag. inclusions partly resorbed micrographic rims
PLAGIOCLASE	23-26	turbid in plain light	0.5-3.0 mm avg. 1.5	subhedral - euhedral laths	$2V_x > 60°$ $An_{(58-20)}$ avg. 48 strong zoning complex twinning	saussurite & sericite along specific zones	conspicuous albite rims alteration not as severe as in core plagioclase inclusions in microperthite
ACTINOLITE	13-18	pale green	1.0-2.5 mm	subhedral, frayed & ragged pseudomorphs after pyx.	$2V_x$ = 74° $Z \wedge c$= 14-15° pleochroic: X= yell. green Y= pale yellow Z= blue green	biotite chlorite	sieve-textured with alteration products of biotite and chlorite relict cores of pyroxene inclusions: plagioclase
BIOTITE	10-13	med. brown	0.5-2.0 mm	subhedral, platy laths with ragged edges	$2V_x$ = 0° pleochroic: X=Y= pale yell. Z= med. brown	chlorite rutile	acicular rutile grains in chlorite alteration quartz inclusions along borders
QUARTZ	7-10	clear	0.5-3.0 mm avg. 1.5	anhedral, subangular grains and interstitial stringers	$2V_z$ = 0° mod. undulous ext.	none	internal microfractures myrmekitic texture in plag. borders minute inclusions in biotite rims
PYROXENE	2-4	colorless	0.5-2.0 mm	relict cores in actinolite local indv. grains	$2V_z < 60°$ oblique ext. mod. birefrng. 90° cleavage	actinolite	relict cores in actinolite

TABLE 2. Mineralogy of the transitional zone

Plagioclase varies little in modal percent from the pluton's core. However, it is not as pervasively altered, as is commonly rimmed by thin, discontinuous albite, which is not as conspicuous in the core. Minor myrmekite along plagioclase contacts with K-spar are also more conspicuous.

Quartz occurs as distinct, anhedral grains as in the core, but is more typically found as interstitial, lobate-masses and stringers surrounding other major rock-components. It also occurs as minute inclusions along the periphery of biotite grains, giving a fringed, or scalloped, appearance to the biotite. Chlorite, altering from biotite, contains radiating, hair-like needles of rutile (?).

Actinolite pseudomorphs, although appreciably more abundant, do not exhibit any textural features not found in the core. Universal-stage measurements replicate those previously obtained from the core.

Paragenesis: Textural and mineralogical discrepancies between the core and transitional zone are not related to differences in paragenesis, but to their varying degree of contamination by the mafic-monzonite rim. The rim's influence on the main plutonic-body gradually diminishes beyond the 50 meters of representative transitional-zone rock. The transitional zone reflects the maximum mineralogical and textural modifications achieved through interaction of the core magma with that of the mafic rim. Its paragenetic sequence, however, is identical to that of its parent rock, the quartz-bearing monzonite core (Figure 5).

Mafic-Monzonite Rim

The mafic rim is a dense, dark-grey, homogeneous, fine- to medium-

grained rock containing 33-38% poikilitic orthoclase, 22-27% euhedral, normally-zoned plagioclase (An_{61-29}), 11-13% prismatic hypersthene, 11-13% prismatic salite, 5-7% reddish-brown biotite, 4-6% pale-green actinolite, 2-4% interstitial quartz, 1-3% altered olivine, 1-2% opaque minerals, and minor apatite and chlorite. The rock is holocrystalline, but individual minerals are difficult to distinguish in hand sample because of the dark color and poikilitic nature of the felsic constituents. Iridescent labradorite grains and shiny biotite plates cause fresh surfaces to sparkle in sunlight.

In thin-section, the rock displays a seriate texture, in which different mineral components vary gradually in size. Mafic minerals and poikilitic orthoclase rarely exceed 3.0 mm in length, and plagioclase and quartz average less than 1.5 mm. The rock is texturally distinct from both the core and transitional zone, but displays important mineralogical similarities that suggest an intimate relationship among the three zones. Petrographic characteristics of the rim's major minerals are summarized in Table 3.

Orthoclase, as in the core and transitional zone, is the dominant mineral component of the mafic rim. Microperthite is exceedingly rare, however, and the mineral does not exhibit pervasive kaolin alteration. It occurs as anhedral, rounded grains enclosing fine- to medium-grained plagioclase laths, biotite, pyroxenes, acicular apatite, and opaque minerals. Micrographic intergrowths are prevalent, and its $2V_x$ of 43-47° is somewhat lower than those for either the core or transitional zone.

Plagioclase is notably finer-grained, more clacic, and less altered than in the core or transitional zone. It occurs as fine- to medium-

MINERAL	%	COLOR	SIZE	HABIT	OPTICAL PROPERTIES	ALTERATION PRODUCTS	DISTINGUISHING CHARACTERISTICS
ORTHOCLASE	33-38	slightly turbid	1.0-3.0 mm	highly poikilitic anhedral, rounded grn.	$2V_x$ = 35-40° Carlsbad twins micrographic	none	poikilitic, optically continous grains enclose fine to med. grained plag., cpx, and opx resorbed plagioclase inclusions
PLAGIOCLASE	22-27	dusty in plain light	0.5-1.5 mm avg. 1.0	well-formed, euhedral laths	$An_{(61-29)}$ avg. 53 $2V_x > 60°$ complex twins	minor calcite & sericite	strong normal zoning ophitic texture in cpx and opx inclusions in K-spar
HYPERSTHENE	11-13	lt. pink & lt. green	0.5-3.5 mm avg. 2.5	poikilitic, subhedral, prismatic grains	$2V_x$ = 60-62° pleochroic: X= lt. pink Y= lt. yellow Z= lt. green	actinolite rims serpentine green biotite opaques	ophitic texture with plagioclase laths ragged appearance encloses olivine grains ubiquitous actinolite rims
SALITE	11-13	lt. brown	0.5-3.5 mm avg. 2.5	poikilitic, subhedral, prismatic grains	$2V_z$ = 56° $Z\wedge C$= 42° mod. birefrg.	actinolite rims green biotite opaques	ophitic texture with plagioclase laths associated with hypersthene and olivine simple twins
BIOTITE	5-7	reddish brown	0.5-3.5 mm avg. 2.0	subhedral, elongate plates and rounded end-sections	$2V_x$ = 0° pleochroic: X=Y= straw yell. Z= red-brown	minor chlorite opaques along cleavage planes	embayed by plag. laths, opx, cpx, and acicular apatite grains quartz inclusions along rims inclusions: rutile, plag., zircon
ACTINOLITE	4-6	pale green	0.5-1.0 mm	rims on cpx and opx	$2V_x$ = 74° $Z\wedge C$= 14-15° low-mod. birefrg.	chlorite biotite	pleochroic: X= yellowish green Y= pale yellow Z= blue green alteration rims on cpx & opx
QUARTZ	2-4	clear	0.5-1.0 mm	interstitial, anhedral, subangular masses	$2V_z$ = 0° weak undulous ext.	none	fine-grained interstitial masses micrographic patches in K-spar myrmekitic edges in plag. inclusions: minute plag. & K-spar
OLIVINE	1-3	pale pink	0.5-3.5 mm	anhedral, rounded grains in opx	$2V_x$ = 85-88° high birefrng. mod. relief fractured	serpentine actinolite iddingsite opaques green biotite	enclosed in opx severe alteration along internal fractures

TABLE 3. Mineralogy of the mafic-monzonite rim

grained, euhedral, normally-zoned laths commonly enclosed in, and partly resorbed by, orthoclase. The grains are commonly fringed with myrmekitic borders, and exhibit complex albite, pericline, and Carlsbad twins. Plagioclase also displays an ophitic texture with both salite and hypersthene. Where not included in other minerals, plagioclase occurs as small, loosely-aggregated clusters of randomly-oriented grains.

Salite, a member of the diopside-hedenbergite series, was determined optically on the universal stage. The mineral has $2V_z = 56^o$, and $Z \wedge C = 42^o$, corresponding to a salite composition with 18-23% molar hedenbergite component (Tröger, 1979, p. 82). Salite is the principal clinopyroxene in rocks derived from an alkali-basalt magma (Wilkeson, in Sørenson, 1974, p. 73) and is the pyroxene most commonly found in shoshonitic rock-types (Morrison, 1980).

Salite occurs as pale brown, subhedral, ragged, prismatic grains with ubiquitous rims of pale-green actinolite. Universal-stage determinations give $2V_x = 74^o$, and $Z \wedge C = 13^o$ for the actinolite rims, paralleling optical data obtained for actinolite grains in the core and transitional zones. Salite is commonly embayed by plagioclase laths, and is closely associated with hypersthene.

Hypersthene yields $2V_x = 60\text{-}62^o$ on the universal stage, corresponding to a hypersthene with 67-70% enstatite component (Tröger, 1979, p. 78). It exhibits near-parallel extinction. Hypersthene occurs in subequal amounts with salite, mirrors the clinopyroxene's size and morphological outline, and is rimmed by pale-green actinolite. Its pleochroism of X = pale pink, Y = pale yellow, and Z = light green enables ready recognition. Pervasive alteration, consisting of oxidized, brownish-orange serpentine,

green biotite, and opaque minerals, follows internal fractures. The grains poikilitically enclose plagioclase laths, opque minerals, and olivine grains. Hypersthene is not normally associated with alkaline igneous-rocks (Hyndman, MS, 1982), but is not uncommon in rocks of the shoshonite association (Morrison, 1980).

Biotite forms tabular, platy laths and rounded, pseudohexagonal end-sections. Its distinct reddish-brown color and common inclusions of radiating wisps of rutile suggest that it is slightly more titanium-rich than biotite from the core or transitional zones (Deer, et al., 1966, p. 213). The grains are typically dissected by long, up to 3.0 mm, acicular apatite-needles and plagioclase laths. The rim's biotite is only rarely altered to chlorite.

Olivine, which is always surrounded by hypersthene, is internally fractured and pervasively altered to oxidized serpentine, iddingsite, white mica, green biotite, and opaque minerals. Universal-stage determinations give $2V_x = 85\text{-}88^{o}$, corresponding to 73-82% molar forsterite component (Tröger, 1979, p. 54). It is well within the compositional range for olivines in alkali-basaltic rocks (Fo_{65}-Fo_{80}) (Morrison, 1980). Wilkinson (in Sørenson, 1974, p. 77) notes that olivines coexisting with calcium-rich pyroxenes, such as salite, typically exhibit the higher Fe/Mg ratio of the two minerals.

Paragenesis: The paragenetic sequence of the mafic-monzonite rim is illustrated in Figure 6. Olivine and calcic plagioclase began crystallizing early in the cooling history of the mafic rim because they both occur as inclusions in prismatic hypersthene-grains. Fine- to medium-grained, euhedral plagioclase laths commonly embay both hypersthene and

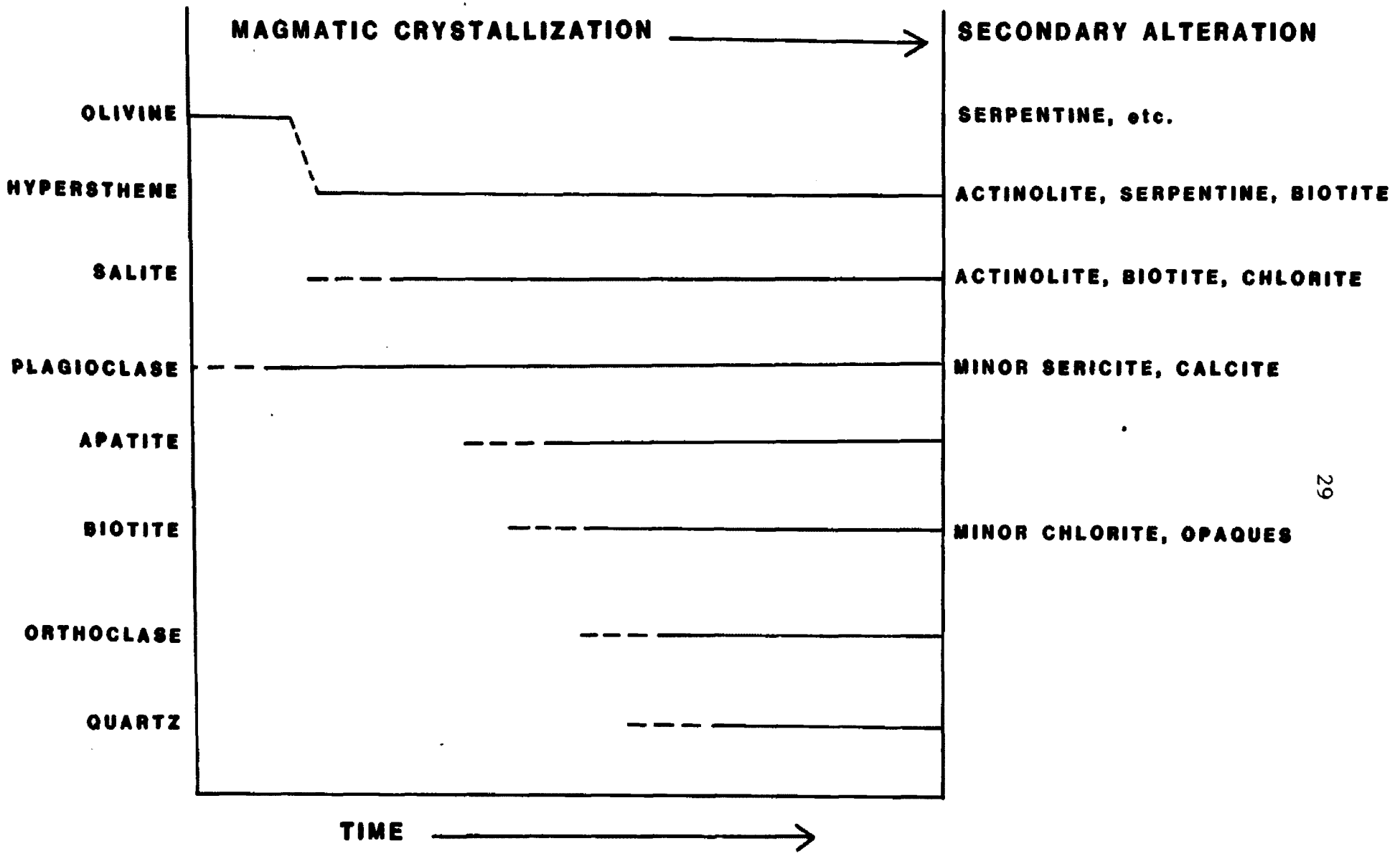


FIGURE 6. PARAGENESIS OF THE MAFIC-MONZONITE RIM

salite, producing a mild ophitic texture to the rock. Olivine is highly fractured and pervasively altered, but optical continuity indicates that the mineral acquired a grain size exceeding 3.5 mm. It is partly resorbed and replaced by hypersthene, and is nowhere found as distinct, independent grains.

Hypersthene, like actinolite in the core, is found closely associated with other minerals, as well as occurring independently of them. In addition to olivine, hypersthene exhibits an affinity towards salite, which occupies the outer-most "zone" of olivine-hypersthene-salite aggregates. Hypersthene and salite, however, are most commonly found as primary, magmatic grains with ubiquitous rims of pale-green actinolite.

Actinolite rims in the mafic monzonite yield optic axial and extinction angles identical to those for actinolite of the core and transitional zone. Universal-stage measurements on actinolite, however, are insufficient for precise compositional determinations. A measurement error of 2V and Z^C of no more than 2^{o} results in an error as large as 10 weight percent (Tröger, 1979, p. 93). The color and angular measurements of the rim's actinolite so closely match those for the core and transitional zone, that it seems plausible that the two have similar compositions.

Biotite, as in the core, began to crystallize after the other mafic components. It is generally well-formed, but exhibits irregular, conformable boundaries where in contact with pyroxene grains. These textural relationships suggest that pyroxene formed before incipient crystallization of biotite. Acicular apatite-needles typically dissect subhedral biotite-laths, indicating that biotite began forming during apatite crystallization.

Unlike the core and transitional zone, initial crystallization of

orthoclase in the mafic rim preceded that of quartz. Quartz rarely occurs as anhedral grains in the mafic rim, but is almost exclusively interstitial-material surrounding the other minerals of the rock. Orthoclase poikilitically encloses all minerals except quartz, although micrographic intergrowths, suggesting simultaneous crystallization, are more abundant than in the core or transitional zone. Plagioclase inclusions in orthoclase display resorbed outlines.

CHAPTER IV

CHEMICAL COMPOSITION

General Comments

Seven representative samples of the Ringing Rocks pluton were collected for whole-rock chemical analyses. Sample locations are indicated in Figure 3. The rocks were crushed and sent to Washington State University, Pullman, where molecular-oxide weight-percent values were determined by x-ray fluorescence. Weight-percent values for ferric and ferrous oxide were calculated from total iron assuming a standard Fe^{+3}/Fe^{+2} ratio of 1:1.145. Eleven major-oxide concentrations for the pluton's three zones are summarized in Table 4.

Weight-percent concentrations can be misleading because they tend to accentuate values for elements with the higher atomic-weights, such as iron. Major-element variations in rock compositions are better illustrated using the standard-cell method of Barth (1948). Major-oxide weight-percent values are converted to cation proportions on the basis of a standard unit-cell of 100 oxygen anions. This method presumes that the gross oxygen-content of the rocks remains relatively constant. Compositional trends are in terms of major-cation concentrations, which more accurately reflect the chemical behavior of magmatic rocks. Whole-rock analyses, therefore, are recalculated to standard-cell variations in Table 4.

CIPW normative minerals for the pluton's three zones were determined

on the University of Montana's computer using the NORM 2 program. Normative minerals, based on molecular-oxide weight-percent values, are listed in Table 5.

Major-Element Trends

Major-element variations among the pluton's three zones concur with modal-mineralogy changes in thin-section. The pluton exhibits a marked enrichment in calcium, magnesium, and total iron, and a corresponding depletion in potassium, aluminum, and silicon as the mafic rim is approached (Figure 7). Sodium remains essentially unchanged. Enriched elements are reflected in increasing contents of calcic-pyroxene, calcic-plagioclase, actinolite, and, in the rim, iron- and magnesium-bearing orthopyroxene and olivine. Depleted elements correspond to a decrease in quartz and potassium feldspar. The relatively uniform sodium-content of the pluton reflects the even distribution of plagioclase among the pluton's three zones. This is also seen in CIPW normative-mineral contents where albite (ab) and anorthite (an) remain virtually unchanged throughout the pluton (Table 5).

Figure 7 plots the number of cations per 100 anions against distance, in meters between indicated sample locations. Chemical trends strongly suggest that the intermediate composition of the transitional zone is a chemical hybrid of the quartz-bearing monaonite core and mafic-monzonite rim. It is further evident from Figure 7 that the influence of the mafic rim on the core does not abruptly stop at the transitional zone. Chemical variations support field and petrographic evidence that the contact between the core and transitional zone is completely gradational.

TABLE 4. Chemical analyses of the Ringing Rocks pluton converted to cations per 100 anions. Locations of samples shown on Figure 3.

Sample No.	1	2	3	4	5	6	7
Location	core	core	core	trans. zone	trans. zone	mafic rim	mafic rim
SiO_2	65.74	64.55	63.69	59.61	59.72	56.42	56.21
TiO_2	0.47	0.50	0.54	0.62	0.60	0.63	0.65
Al_2O_3	15.04	14.87	14.42	14.67	14.55	13.70	13.73
Fe_2O_3	1.94	2.07	2.24	2.85	2.84	3.39	3.31
FeO	2.22	2.37	2.57	3.27	3.25	3.88	3.79
MnO	0.07	0.09	0.09	0.11	0.11	0.13	0.13
MgO	3.70	4.11	4.76	6.32	6.74	9.33	9.23
CaO	3.15	3.49	3.90	5.07	5.25	5.95	6.00
Na_2O	2.67	2.82	2.68	2.94	2.78	2.76	2.99
K_2O	4.78	4.89	4.83	4.16	3.82	3.48	3.62
P_2O_5	0.22	0.24	0.29	0.37	0.34	0.34	0.35
Si	30.57	29.93	29.52	27.47	27.52	25.80	25.66
Ti	0.16	0.17	0.19	0.21	0.21	0.22	0.21
Al	5.48	5.40	5.24	5.30	5.25	4.91	4.91
Fe^{+3}	0.45	0.48	0.52	0.66	0.65	0.77	0.75
Fe^{+2}	1.72	1.80	1.99	2.51	2.50	2.96	2.88
Mn	0.06	0.07	0.07	0.09	0.09	0.10	0.10
Mg	5.16	5.72	6.62	8.74	9.33	12.80	12.64
Ca	3.14	3.47	3.87	5.01	5.18	5.83	5.87
Na	4.81	5.06	4.81	5.24	4.96	4.86	5.28
K	5.67	5.79	5.72	4.89	4.49	4.06	4.22
P	0.03	0.04	0.05	0.06	0.05	0.05	0.05

TABLE 5. CIPW normative minerals for the Ringing Rocks pluton. Location of samples shown on Figure 3.

Sample No.	1	2	3	4	5	6	7
Location	core	core	core	trans. zone	trans. zone	mafic rim	mafic rim
q	19.44	16.09	14.95	7.83	9.00	2.28	0.28
or	28.25	28.90	28.54	24.58	22.58	20.57	21.39
ab	22.25	23.86	22.68	24.88	23.52	23.36	25.30
an	14.19	13.47	13.05	14.55	15.94	14.72	13.35
di	---	1.80	3.49	6.49	6.24	9.94	11.16
hy	11.04	11.37	12.35	15.50	16.67	22.07	21.11
mt	2.81	3.00	3.25	4.13	4.12	4.92	4.78
il	0.89	0.95	1.03	1.18	1.14	1.20	1.23
ap	0.51	0.56	0.67	0.86	0.79	0.79	0.82
c	0.27	--	--	--	--	--	--

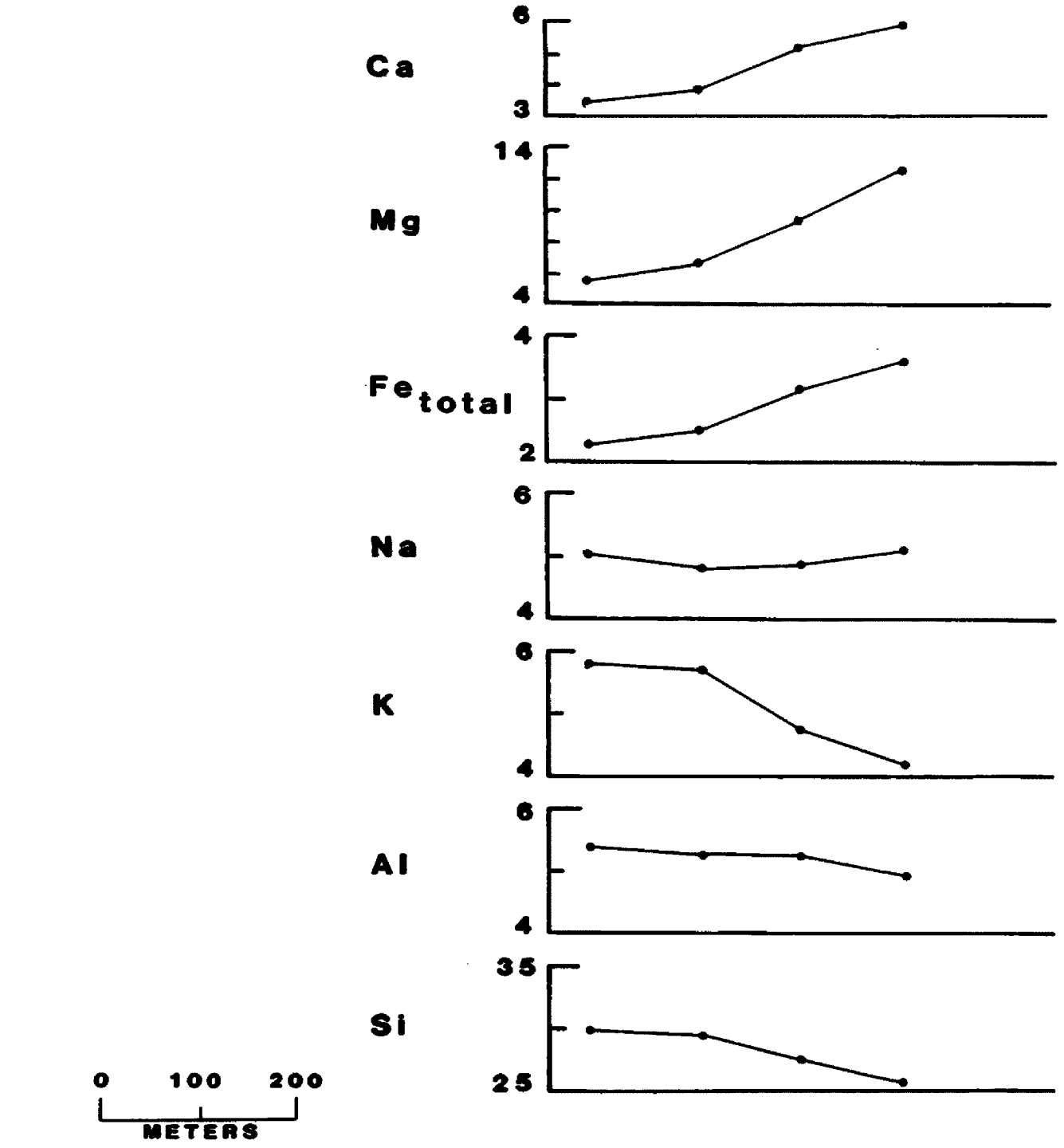
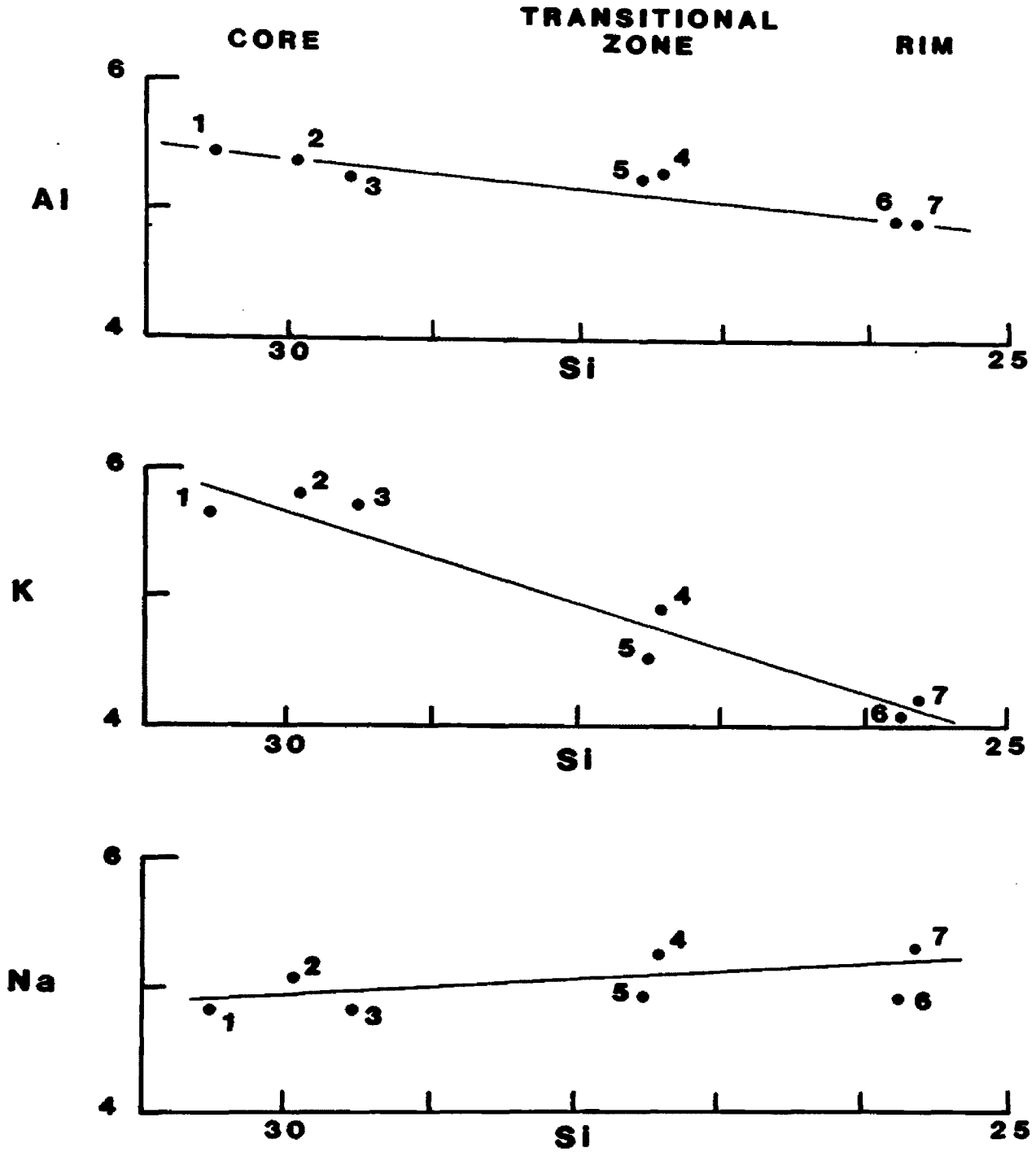


FIGURE 7.

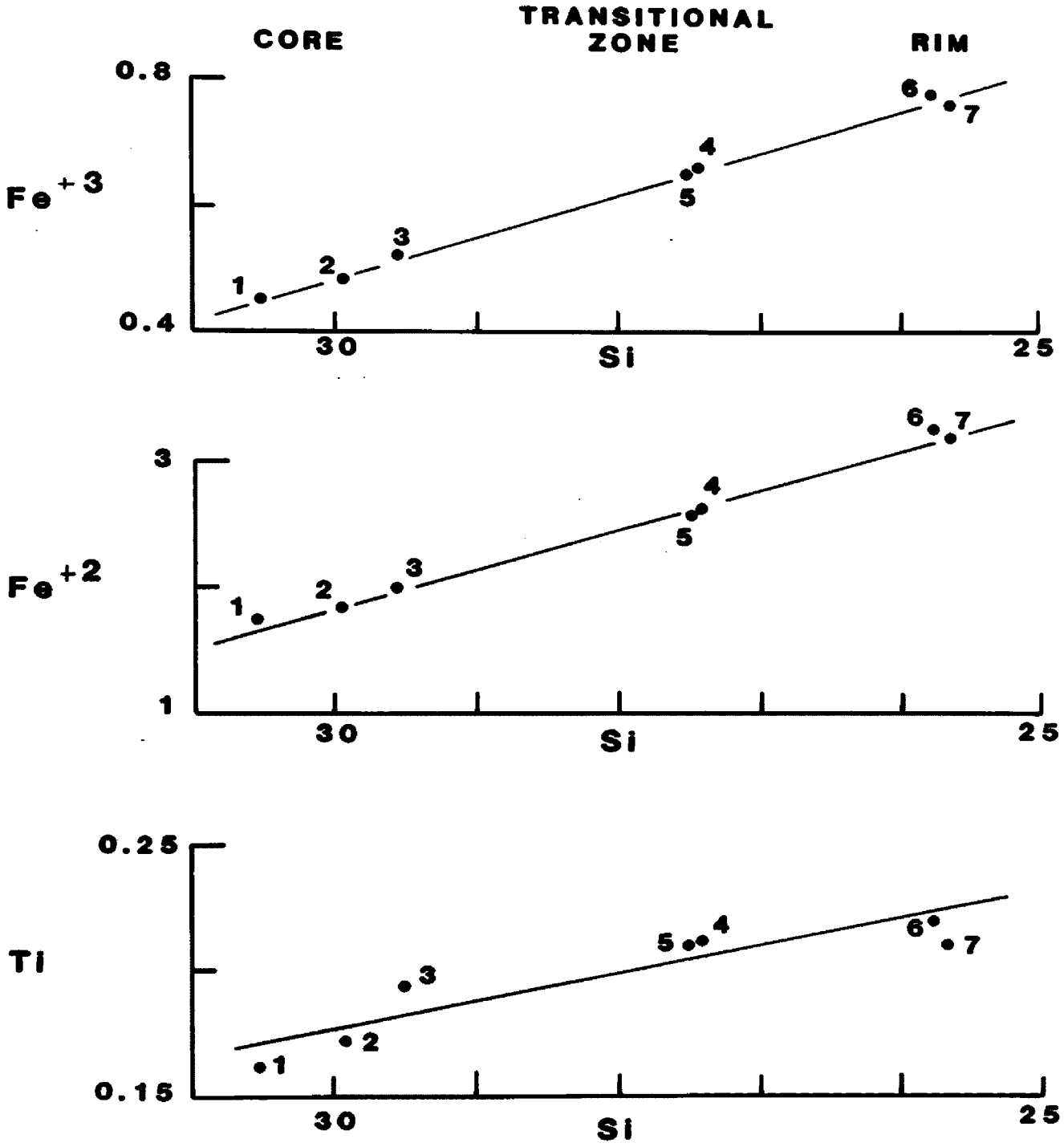
VARIATIONS IN CATIONS PER 100 ANIONS WITH DISTANCE.

Near-linear trends for the major cation-components of the Ringing Rocks pluton are evident in variation diagrams plotted against silicon content. Figure 8 shows nearly straight-line decreases in aluminum and potassium with decreasing silicon content towards the mafic rim. Sodium, in Figure 8, remains almost unchanged despite variations in silicon content. Figures 9 and 10 display near-linear increases in total iron, titanium, magnesium, and calcium with a corresponding decrease in silicon content. These plots, in addition to Figure 7, illustrate the chemical affinity of the transitional zone for both the core and mafic rim. Clearly, the quartz-bearing monzonite core, adjacent to the mafic-monzonite rim, has been modified into an intermediate chemical-composition represented by the transitional zone.



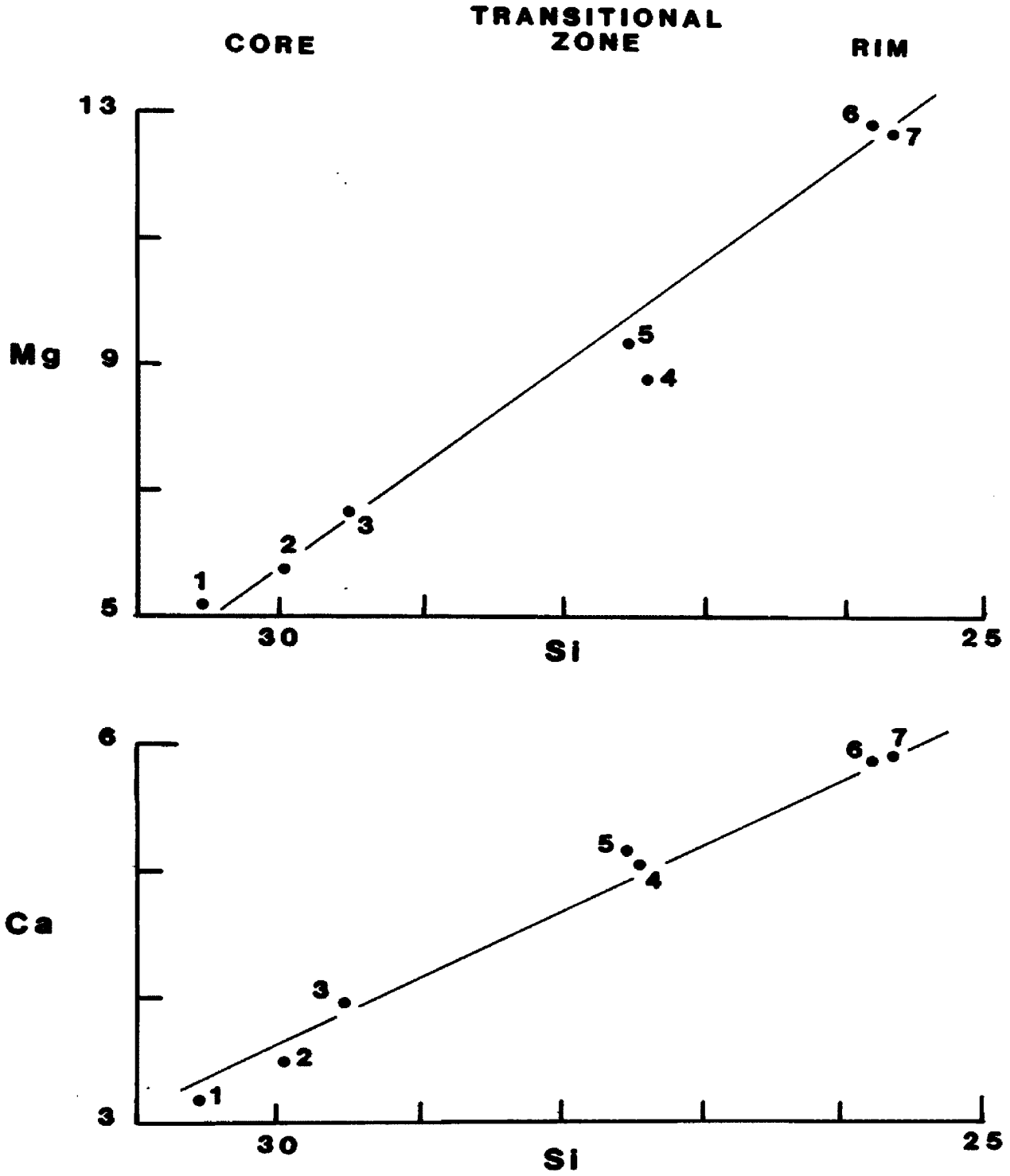
VARIATIONS IN CATION CONCENTRATIONS PER 100 ANIONS FOR Al, K, AND Na.

FIGURE 8.



VARIATIONS IN CATION CONCENTRATIONS PER 100 ANIONS FOR Fe^{+3}, Fe^{+2}, AND Ti.

FIGURE 9.



VARIATIONS IN CATION CONCENTRATIONS PER 100 ANIONS FOR Mg AND Ca.

FIGURE 10.

CHAPTER V

PETROGENESIS

Contemporaneity and Magma Mixing

As established above in the discussion of field relations, Ringing Rocks pluton does not appear to be a layered igneous-intrusion of vertically varying rock units. This is supported by the absence of cumulate texture in the mafic monzonite, which would presumably constitute the lowest stratigraphic member of the pluton. Formation of the pluton's three zones by fractional crystallization does not seem plausible given the small size of the intrusion. Cooling and crystallization would proceed too rapidly for magmatic differentiation to occur (Hyndman, MS, 1982). Moreover, potassium feldspar, a late-stage differentiate in fractional crystallization, is the dominant mineral component of the mafic monzonite.

Chemical compatibility to rocks of the main magma-series of the Boulder batholith suggests that the quartz-bearing monzonite core and mafic-monzonite rim may be comagmatic. The close spatial association of the core and rim certainly requires special considerations for emplacement. However, interpreting field relationships as evidence for comagmatism is equivocal. The unique juxtaposition of rock-types could conceivably be structurally controlled, resulting from the pluton's emplacement along a major prebatholithic shear-zone. Furthermore, the quartz-bearing monzonite core is chemically and mineralogically compatible to rocks of the calc-alkaline association, whereas the mafic-monzonite rim exhibits an affinity

to rocks of the potassium-rich shoshonite association. It seems more probable that the close association of the core and mafic rim is structurally related, and that the core and rim are two, separate igneous-intrusions that did not originate from a common parent magma. This does not dismiss the possibility, however, that the primary magma that formed the mafic monzonite may have induced partial melting during its crustal ascent and formed the quartz-bearing monzonite of the pluton's core.

Whichever the case, field relations indicate that the two main rock-types of Ringing Rocks pluton were emplaced in the same general area at about the same time. Near contemporaneity is suggested by the lack of cross-cutting relationships that would indicate a time sequence. The mafic-monzonite rim conforms to the general outline of the quartz-bearing monzonite core, and no chill zones separate the two intrusions. Moreover, the presence of the gradational, intervening transitional zone, rather than sharp contacts, indicates that the core and mafic rim are about the same age.

The close relationship of the two intrusions is evident. That they somehow combined to form the transitional zone, however, is more difficult to illustrate. Magma mixing, in its strictest sense, is the process whereby two or more compositionally-distinct magmas mix together to form a single magma of reasonably-uniform composition (Anderson, 1976). Eary crystalline-phases from the individual magmas commonly display disequilibrium relationships in their new environment. The magmas' melts, however, blend together to form a fairly uniform composition. This latter restriction establishes the distinction between magma mixing and contamination by assimilation, viz., contributing contaminants must be partly molten at the time of mixing

(Anderson, 1976).

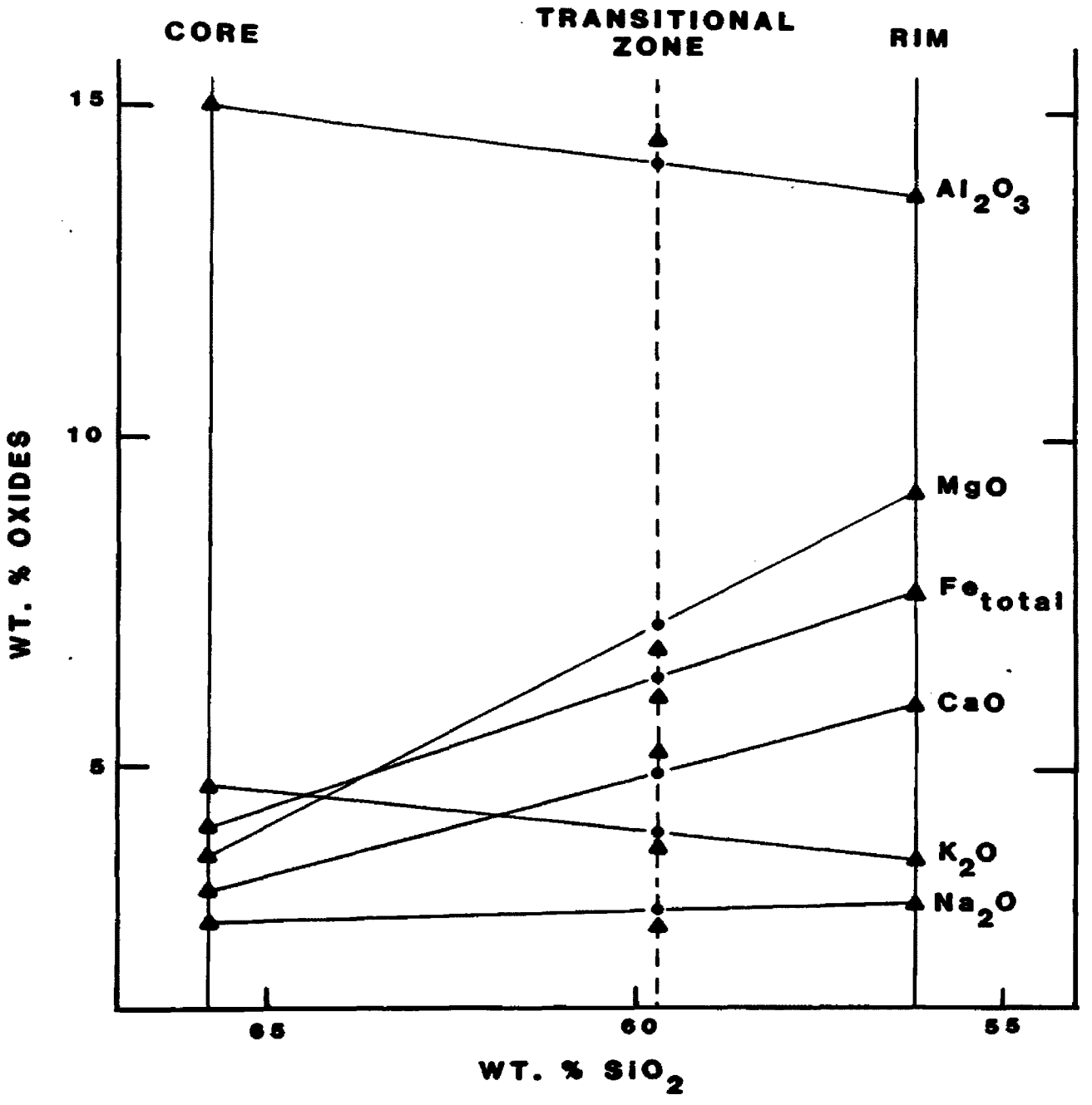
Although relict pyroxene grains in the core and transitional zone cannot be unequivocally ascribed to magma-mixing, textural relationships indicate that they are not in equilibrium with the surrounding mineral assemblage. Pyroxene is invariably resorbed and replaced by actinolite. Such compositional adjustments suggest that pyroxene re-equilibrated with an environment in which it did not originate. Given the presence of the intermediate transitional-zone, it does seem plausible that the relationship exhibited by this early mineral component resulted from mechanical mixing of the two magmas.

The intermediate chemical composition of the transitional zone suggests that it is the hybrid product of the two, compositionally-distinct intrusions. Figure 11 plots major-oxide weight-percent values for the core and mafic rim against their respective SiO_2 contents. Corresponding major oxides are connected with a straight line to show their general trend through the pluton. The dashed line represents a hypothetical transitional-rock containing 59.7% SiO_2. Intersections with the chemical trends give idealized major-oxide contents for its intermediate composition. These values are compared with those for the true transitional-zone and show a remarkable correlation. It is apparent that the representative transitional-zone contains intermediate contents of all major oxides.

The narrow zone of representative transitional-rock indicates that the two intrusions did not mix extensively. The mafic-monzonite rim undoubtedly contained a significant proportion of crystalline-phases since most of its mineral components are earlier in Bowen's reaction series than the most calcic zone of the core's plagioclase. Magma-mixing was

FIGURE 11.

INTERMEDIATE COMPOSITION OF THE TRANSITIONAL ZONE



HYPOTHETICAL TRANS. ZONE WITH 59.7% SiO_2 (●)		TRUE TRANS. ZONE WITH 59.7% SiO_2 (▲)
Al_2O_3	14.20%	14.58 %
MgO	7.20	6.74
Fe_{total}	6.40	6.09
CaO	5.00	6.25
K_2O	4.05	3.90
Na_2O	2.68	2.78

predominantly a mechanical process with only minor chemical diffusion between melts. This is supported by the incomplete equilibration of relict pyroxene-grains in the core and transitional zone. Also, plagioclase in the transitional zone does not display reverse zoning. This suggests that the liquid of the core did not undergo substantial compositional changes through interaction with the mafic rim (Eichelberger, 1975). Despite its limited extent, however, magma-mixing of the two intrusions resulted in the formation of an intermediate, chemically-distinct rock-type.

Petrogenesis of the Quartz-Bearing Monzonite Core

The genetic relationship between the pluton's core and the Boulder batholith is not as obvious as their spatial and temporal association would suggest. The core is mineralogically, texturally, and temporally similar to granodiorites of the Radar Creek pluton. This pluton, located less than 2 kilometers south of Ringing Rocks pluton (Figure 2) is predominantly equigranular and contains hornblende with relict cores of augite (Tilling, 1964). K-Ar determinations on biotite and hornblende yielded a concordant age of 77-74 m.y., establishing the pluton as one of the earlier intrusions of the Boulder batholith (Tilling, et al., 1968). Hamilton and Myers (1974) believe that the Radar Creek Granodiorite may continue beneath the Elkhorn Mountains Volcanics and form the Wilson Park pluton 20 kilometers to the north (Figure 2). Ringing Rocks pluton is directly along strike between the two plutons.

The chemical composition of the Radar Creek pluton, however, is distinctly different from that of the quartz-bearing monzonite core. Figure 12 is a ternary K_2O-Na_2O-CaO variation diagram showing the

compositional fields of the main and sodic magma-series of the Boulder batholith (Tilling, 1973). The quartz-bearing monzonite core (samples 1-3) exhibits a chemical compatibility for the more potassic, main-series plutons, while the Radar Creek pluton is associated with the chemically distinct sodic series. The high potassium-content of the core is especially evident in Figure 13, which plots K_2O weight-percent values against SiO_2 content. The Radar Creek pluton, although containing a similar silica-content, is significantly lower in potash than the quartz-bearing monzonite core.

Tilling (1973) believes that the chemical disparity between plutons of the two magma-series indicates that the batholith was derived from at least two different magma-sources. This suggests that the core of the Ringing Rocks pluton is not an extension of, or related to, the chemically-incompatible granodiorites of the Radar Creek pluton. Although the core cannot be genetically equated with any particular pluton, it is probably related to the magma source that formed the main-series plutons of the Boulder batholith.

Petrogenesis of the Mafic-Monzonite Rim

The pluton's rim, like other mafic rocks associated with the batholith, falls within the field of the main magma-series (Figures 12 and 13). Mafic rocks occur predominantly as small plugs and dikes along the periphery of the main batholith, and are generally associated with the earlier, granodioritic plutons. The largest mafic body is the Kokoruda Ranch complex, located along the northeastern border of the Butte Quartz Monzonite (Figure 2). It consists of a wide variety of rock types, several of which

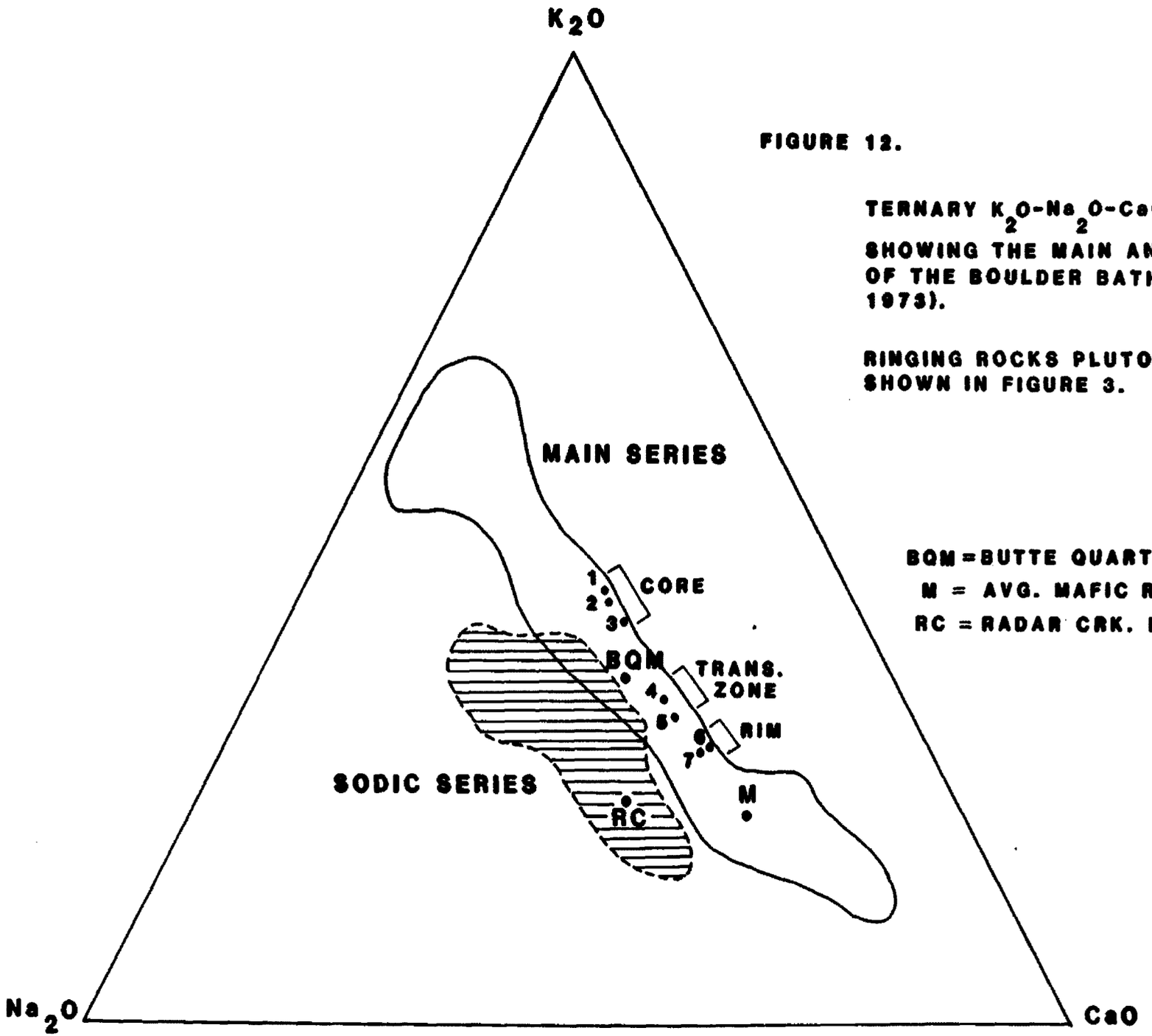
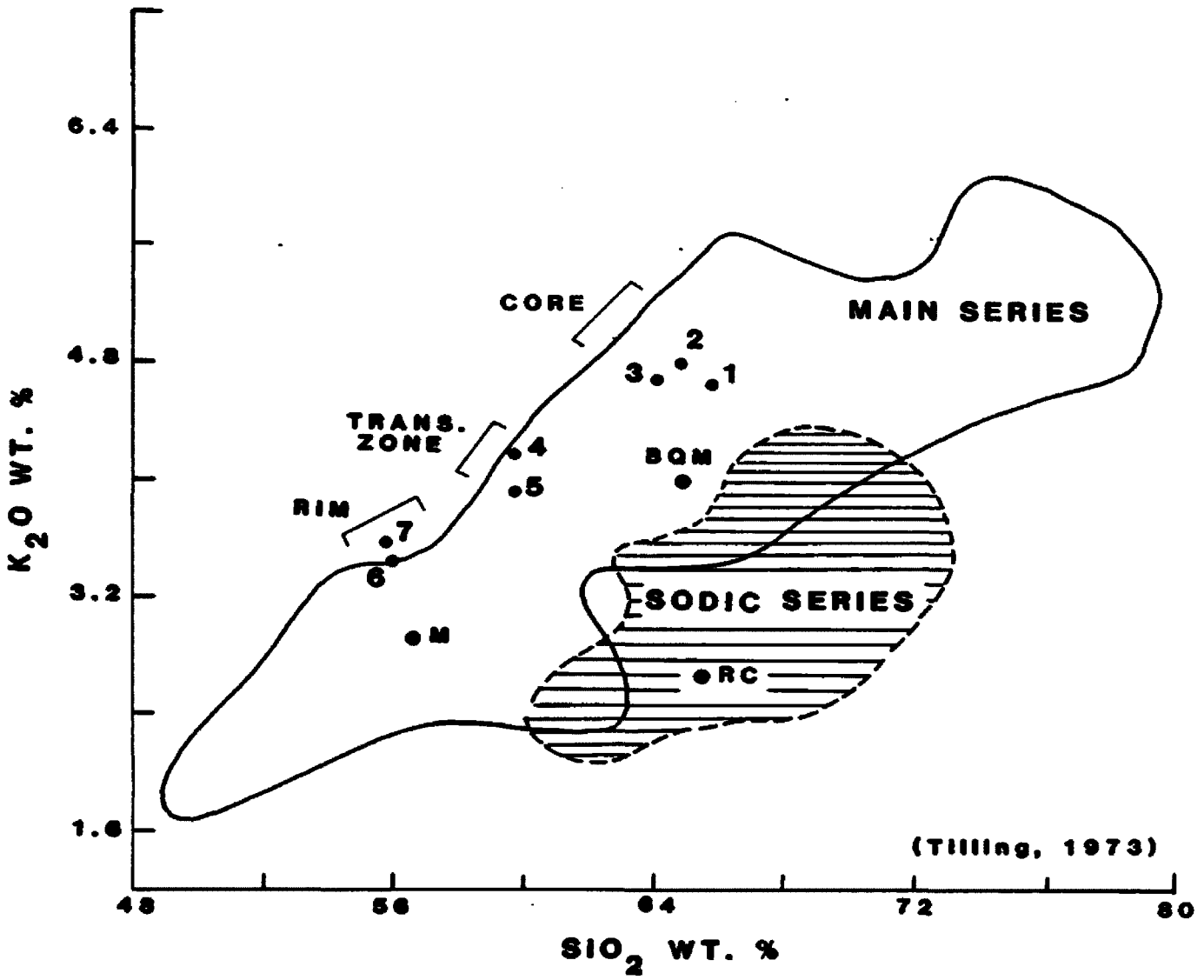


FIGURE 12.

TERNARY K_2O-Na_2O-CaO DIAGRAM SHOWING THE MAIN AND SODIC SERIES OF THE BOULDER BATHOLITH (Tilling, 1973).

RINGING ROCKS PLUTON SAMPLE LOCATIONS SHOWN IN FIGURE 3.

BQM = BUTTE QUARTZ MONZONITE
M = AVG. MAFIC ROCK
RC = RADAR CRK. PLUTON



K_2O-SiO_2 VARIATION DIAGRAM SHOWING THE MAIN AND SODIC MAGMA SERIES FIELDS OF THE BOULDER BATHOLITH. RINGING ROCKS PLUTON SAMPLES ARE NUMBERED. THEIR LOCATIONS ARE SHOWN IN FIGURE 3.

FIGURE 13.

are nearly identical to the mafic-monzonite rim (Smedes, 1966). An average chemical-composition of the Kokoruda Ranch complex, from Smedes (1966), is plotted as "M" on the variation diagrams of Figures 12 and 13. A characteristic feature of the mafic rim, and similar mafic-rocks, is that they are mineralogically and chemically compatible with rocks of the shoshonite association.

Shoshonites are a group of near silica-saturated, potassium-rich rocks that exhibit characteristics of both the calc-alkaline and alkaline suites (Morrison, 1980). They typically occur as volcanic rocks in young island-arc terrains, but plutonic equivalents have been recognized along continental margins (Jakes and White, 1972) and within the stable craton (Woods, 1976). There appears to be an intimate association between shoshonites and calc-alkaline rocks becuase the two are commonly found together and display gradational compositional characteristics (Joplin, 1968).

Chemical characteristics that establish shoshonites as a distinct rock-association include the following (Morrison, 1980):

1) near silica-saturation (low normative Ne or Q);
2) low iron enrichment (flat trend on AFM diagram);
3) high total alkalies ($Na_2O + K_2O$ greater than 5%);
4) high K_2O/Na_2O (greater than 1.0% at 55% SiO_2);
5) low TiO_2 (less than 1.3%);
6) high but variable Al_2O_3 (14-20%);
7) high Fe_2O_3/FeO (greater than 0.5%).

Shoshonites are distinguished from the calc-alkaline association by containing higher $Na_2O + K_2O$, K_2O/Na_2O and K_2O/SiO_2, and lower normative

silica. They differ from the alkali-basalt association by exhibiting higher normative silica, Fe_2O_3/FeO, $Na_2O + K_2O$, and lower iron-enrichment and TiO_2 content.

Shoshonitic rocks are subdivided according to their SiO_2 content, ranging from basaltic shoshonites, with less than 53% SiO_2, to dacite, containing more than 63% SiO_2. According to this classification (Joplin, 1968), the mafic-monzonite rim falls within the basaltic-andesite group with 53-57% SiO_2. Chemical characteristics of this shoshonitic rock-type are compared with the mafic-monzonite rim in Table 6. Except for a relatively low Al_2O_3 content and high normative-hypersthene value, the mafic-monzonite rim is chemically compatible with shoshonitic basaltic andesites. Morrison (1980) notes, however, that shoshonitic rocks from cratonic settings generally contain more orthopyroxene and biotite, and less olivine, than shoshonites in island-arc environments.

Mineralogically, shoshonitic basaltic andesites commonly contain phenocrysts of unresorbed olivine (Fo_{65}-Fo_{85}), calcium-rich clinopyroxene (augite to salite), plagioclase (An_{85-50}), hypersthene, and hornblende (Morrison, 1980). Groundmass material in volcanic rocks is predominantly sanidine, plagioclase and clinopyroxene, with local biotite and hypersthene. Olivine does not occur in the groundmass. Figure 14 shows the compositional range for clinopyroxene, orthopyroxene, and olivine for the shoshonite rock association (solid lines) (Morrison, 1980), and mafic-monzonite rim (dashed lines) in the pyroxene tetrahedron. The minerals in the mafic rim, as determined on the universal stage, fall within the compositional range for those of the shoshonite association. Unlike olivine phenocrysts in shoshonitic and alkali-basaltic rock-types, however,

TABLE 6. Major-oxide and normative-mineral contents of shoshonitic basaltic andesites (Morrison, 1980) and the mafic-monzonite rim.

	Shoshonite Basaltic Andesite	Mafic-Monzonite Rim
SiO_2	53.60 - 56.50	56.32
TiO_2	0.68 - 1.84	0.64
Al_2O_3	14.20 - 20.00	13.72
Fe_2O_3	1.21 - 5.92	3.35
FeO	1.30 - 5.16	3.84
MnO	0.07 - 0.18	0.13
MgO	3.75 - 9.20	9.28
CaO	3.01 - 7.87	5.98
Na_2O	2.15 - 4.15	2.88
K_2O	2.40 - 6.05	3.55
P_2O_5	0.01 - 1.44	0.34
$K_2O + Na_2O$	6.60 - 7.23	6.43
K_2O/ Na_2O	0.84 - 1.24	1.24
Fe_{total}	6.31 - 7.80	7.19
Fe_2O_3/FeO	0.64 - 1.49	0.87
q	3.23 - 4.73	1.28
or	18.25 - 22.59	20.98
ab	26.76 - 32.84	24.33
an	15.97 - 23.17	14.14
di	1.97 - 8.87	10.55
hy	10.15 - 13.69	20.59
ol	-----	---
mt	2.70 - 4.25	4.85
il	1.16 - 2.63	1.22
ap	1.00 - 1.64	0.81

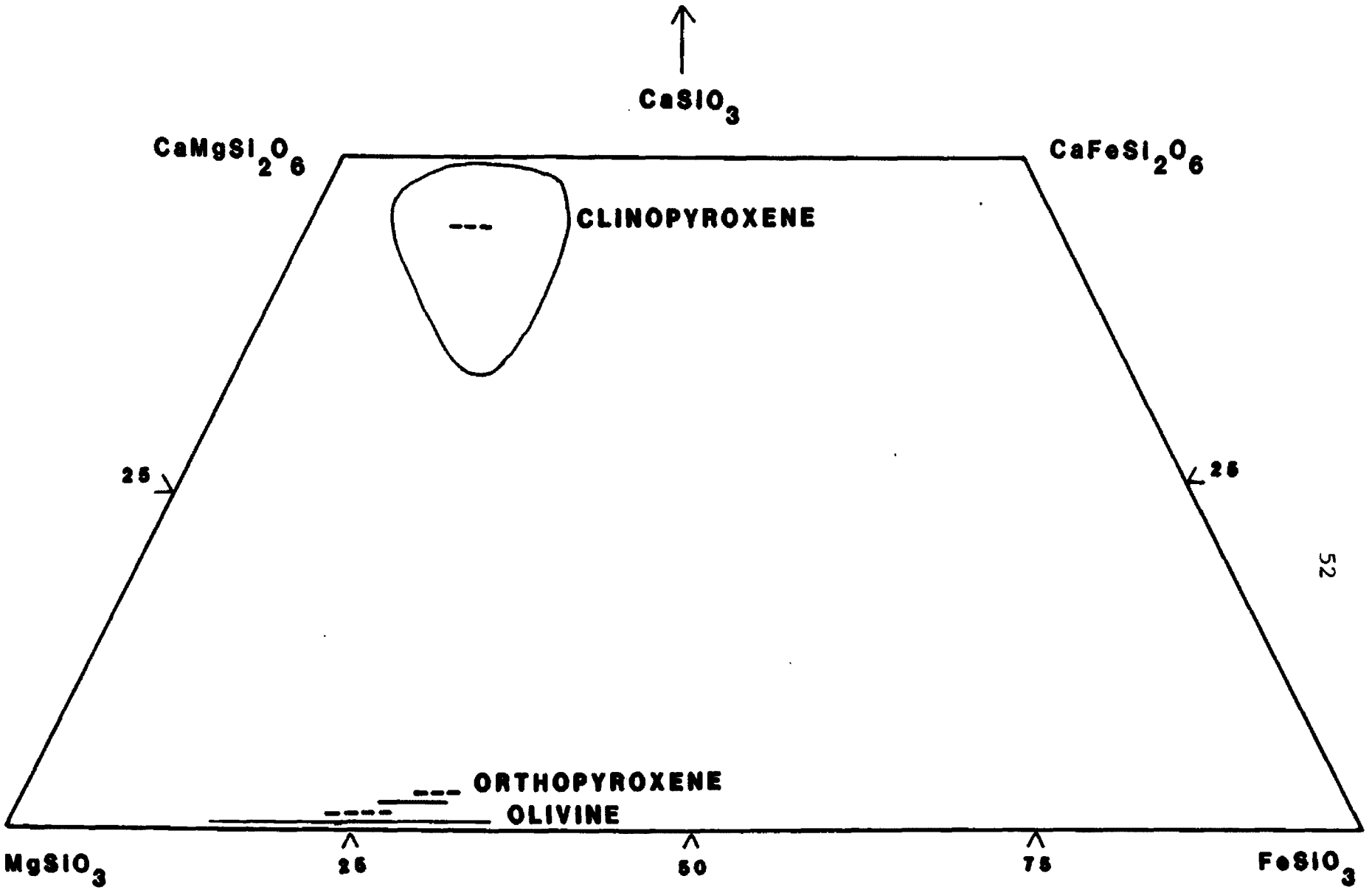


FIGURE 14. COMPOSITIONS OF CLINOPYROXENE, ORTHOPYROXENE, AND OLIVINE FOR THE SHOSHONITE ASSOCIATION (solid lines)(Morrison, 1980) AND MAFIC-MONZONITE RIM OF RINGING ROCKS PLUTON (dashed lines).

olivine in the mafic rim is partly replaced by hypersthene.

The origin of potassium-rich shoshonitic rocks is a subject of little agreement. Their confinement to specific tectonic regimes, however, places some limitations on their possible modes of origin. Shoshonites appear to be restricted to areas that are undergoing, or have undergone, crustal stabilization (Joplin, 1968). They normally occur above the deepest part of the subduction zone, are always on continental crust, and are absent from truly oceanic environments. In addition to spatial restrictions, shoshonites also appear to be temporally controlled, as they are ususally the final stage in an evolving island-arc terrain. In a sequence of tholeiitic to calc-alkaline to high-K calc-alkaline to shoshonitic rock-types, the shoshonite association is younger, stratigraphically higher, and farthest from the oceanic trench (Morrison, 1980).

The location and time sequence of the shoshonite rock association suggest that crustal contamination may play an important role in its formation. Studies on initial Sr^{87}/Sr^{86} ratios for shoshonites and other potassium-rich alkalic rocks indicate that the rocks were influenced by, or derived from, the continental crust (Powell and Bell, 1970). Most models for the origin of potassium-rich magmas involve partial melting of the upper mantle, with subsequent contamination during crustal ascent (Hyndman, MS, 1982). Petrologists have come to believe that potassium and water may exist in the upper mantle in the form of accessory phlogopite (Bravo and O'Hara, 1975). Partial melting of a phlogopite-spinel-, or garnet-bearing, lherzolite could produce a mantle-derived magma with a higher initial K_2O-content than previously suspected. Additional contamination by continental crust could conceivably produce a magma with

a considerable potassium content.

Recent experiments by Watson (1982) indicate than an ascending, mantle-derived magma can selectively absorb the common crustal constituents in which it is most depleted. The experiments investigated the chemical changes resulting from contamination of a molten basalt (50% SiO_2) by a synthetic mixture of "granitic" composition. The mixture, consisting of equal proportions of felsic-components (quartz + K-spar + oligoclase), was immersed in a large reservoir of molten basalt at temperatures well above the basaltic liquidus (1200^{o}-1250^{o} C). The conditions assume that an ascending basaltic magma induces local melting of contacting felsic-crust, as only minor amounts of undissolved quartz and feldspar remained in the melt.

Microprobe traverses across the contributants' interface revealed a significant K_2O increase in the basalt, and only minor enrichment of Na_2O in the immediate zone of mixing. Watson (1982) attributes the selective enrichment of K_2O over Na_2O to its higher activity gradient between the contrasting melts. The initially low concentration of K_2O in the basalt (1.1 wt. %) induces equilibrium partitioning of the element from the felsic melt (5.5 wt. %). The two-liquid equilibrium value for feldspars, according to Watson, is 2:1 to 3:1, substantially lower than the 5:1 concentration ratio exhibited by the experimental granite/basalt. Na_2O concentrations in basalt (3.1 wt. %) and granite (3.1 wt. %), however, do not provide the compositional gradient necessary for significant diffusion between melts.

Watson maintains that once the two-liquid equilibrium value is achieved through elemental diffusion, the only mechanism to further

increase the basalt's potassium-content is bulk assimilation of the granitic rock. This would produce a buffering system against inordinate increases in K_2O concentrations because incorporation of solid granitic-rock would increase the SiO_2 content of the basalt as well. These experiments, therefore, appear to diminish the potassium-contaminating capability of the continental crust. Watson believes that a basalt with an initial SiO_2 content of 50 wt. % would be buffered against further contamination once its K_2O content reached 1.0-1.5 wt. %. This would seem to support an origin for potassium-rich mafic-rocks that involved a parent magma with initially high concentrations of potassium, such as those derived from partial-melting of phlogopite-bearing mantle rocks. Consistently high strontium-isotope ratios for potassium-rich mafic-rocks indicate that the continental crust is probably a factor in their formation. The initial Sr^{87}/Sr^{86} ratios for the mafic-monzonite rim of the Ringing Rocks pluton (0.7069) and Kokoruda Ranch complex (0.7073), for example, do seem to indicate crustal influence in their formation (Doe, et al., 1968). To what extent, however, is open to conjecture.

The mafic-monzonite rim's genetic affinity to the shoshonite association is supported by the rock's chemistry, mineralogy, and tectonic setting. The occurrence of similar potassium-rich mafic-rocks in the Kokoruda Ranch complex indicates that the rim is not an isolated enigma. Unlike most shoshonitic rock-types, however, potassium-rich mafic rocks of the Boulder batholith temporally precede the calc-alkaline rocks with which they are intimately associated. Although this fact cannot be resolved, not all potassium-rich igneous-rocks in apparent association with the Boulder batholith are early, mafic-varieties.

Other Potassium-Rich Rocks of the Boulder Batholith

The northern-most portion of the Boulder batholith consists of satellitic plutons of unknown age and origin (Tilling, 1973) (Figure 2). The largest of these plutons is a porphyritic granodiorite (Knopf, 1957) that intrudes Paleozoic carbonates of the Jefferson Formation and Madison Group (Figure 15). Contact metamorphism created a tactite zone intermittently exposed along most of the pluton's northern border. The contact between the granodiorite and carbonate country-rock is interrupted at three separate locations by small intrusive bodies of leucocratic, potassium-rich monzonite. The Priest Pass Leucomonzonite (Knopf, 1957, 1963) is best exposed on War Eagle Hill, east of Austin, where it forms an elliptical body 6 kilometers in area. Exposure, however, is generally poor, restricted to low-lying outcrop, float, and abandoned prospect-pits. An attempt to map and correlate rock types in this area was discontinued for lack of sufficient outcrop.

The Priest Pass Leucomonzonite is a pinkish-grey, porphyritic, inhomogeneous rock with penetrating dikes of alaskite, pegmatite, and aplite. Thin-section study reveals large, up to 1.0 cm, megacrysts of microperthitic orthoclase (10-15%), and 5.0-7.0 mm phenocrysts of plagioclase (An_{36-33}) (15-20%) in a groundmass of fine- to medium-grained orthoclase (30-35%), plagioclase (15-20%), quartz (8-12%), hornblende (3-5%), and biotite (3-5%). Accessory minerals include magnetite, apatite, sphene, and zircon. The rock is heterogeneous, as its modal mineralogy, most notably its quartz content, varies between, and within, each intrusion.

In the Austin and War Eagle Hill areas, small pods of alkali-syenite separate the leucomonzonite from the tactite zone. The rock is light-grey,

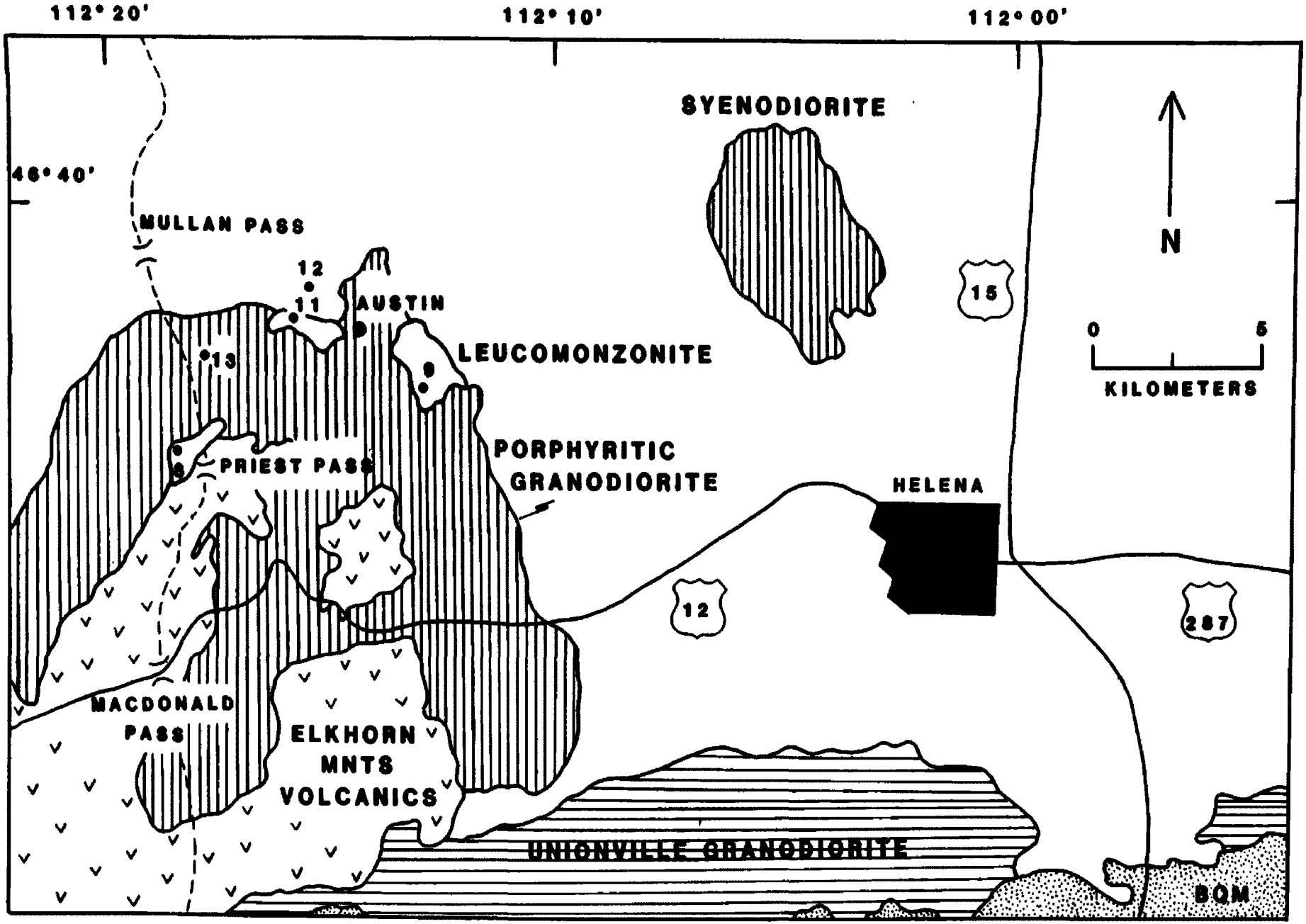


FIGURE 15.

GENERAL GEOLOGIC MAP OF THE NORTHERN PART OF THE BOULDER BATHOLITH SHOWING SAMPLE LOCATIONS OF THE POTASSIUM-RICH ROCKS AND PORPHYRITIC GRANODIORITE.

medium-grained, and in places, is penetrated by thin, discontinuous veins of mauve-colored garnet, pale-green diopside, and scapolite. In thin-section, the rock consists of 90-95% fine- to medium-grained, anhedral to subhedral laths of microperthitic orthoclase. Grains are randomly oriented and display sutured boundaries. Subordinant, fine-grained minerals are 1-3% clinopyroxene (augite), tr-3% plagioclase (An_{31-26}), 1-2% sphene, and tr-1% quartz. Accessory minerals include trace amounts of apatite, chlorite, hematite, and black opaque minerals, along with ubiquitous grains and stringers of secondary garnet. A similar rock-type has been reported in the metasedimentary, tactite-zone that separates the Radar Creek pluton from the Butte Quartz Monzonite (Smedes, in Miller, 1973, p. E-8).

In addition to these two potassium-rich, leucocratic rock-types, small, low-lying outcrops of mafic-syenite occur in the tactite zone of the Austin area. Originally reported as a shonkonite by Knopf (1957, 1963), the rock contains too much plagioclase to fit the literal definition of a shonkonite (Pavelenko, in Sørenson, 1974, p. 281). The rock is dark-grey to black, medium-grained, and equigranular in hand sample. In thin-section, the rock consists of 45-50% medium- to coarse-grained, anhedral, poikilitic microperthitic-orthoclase, 25-30% fine- to medium-grained, poikilitic hornblende, 10-15% fine- to medium-grained, subhedral laths of plagioclase (An_{31-27}), 7-10% fine-grained, anhedral, pale-green diopsidic-augite with abundant rims of amphibole, along with 2-3% predominantly secondary biotite, and minor chlorite, apatite, muscovite, sphene, and Fe-oxides.

Two representative samples of leucomonzonite, and one sample each of alkali-syenite, mafic-syenite, and porphyritic granodiorite were chemically analyzed at Washington State University. Table 7 lists the rocks'

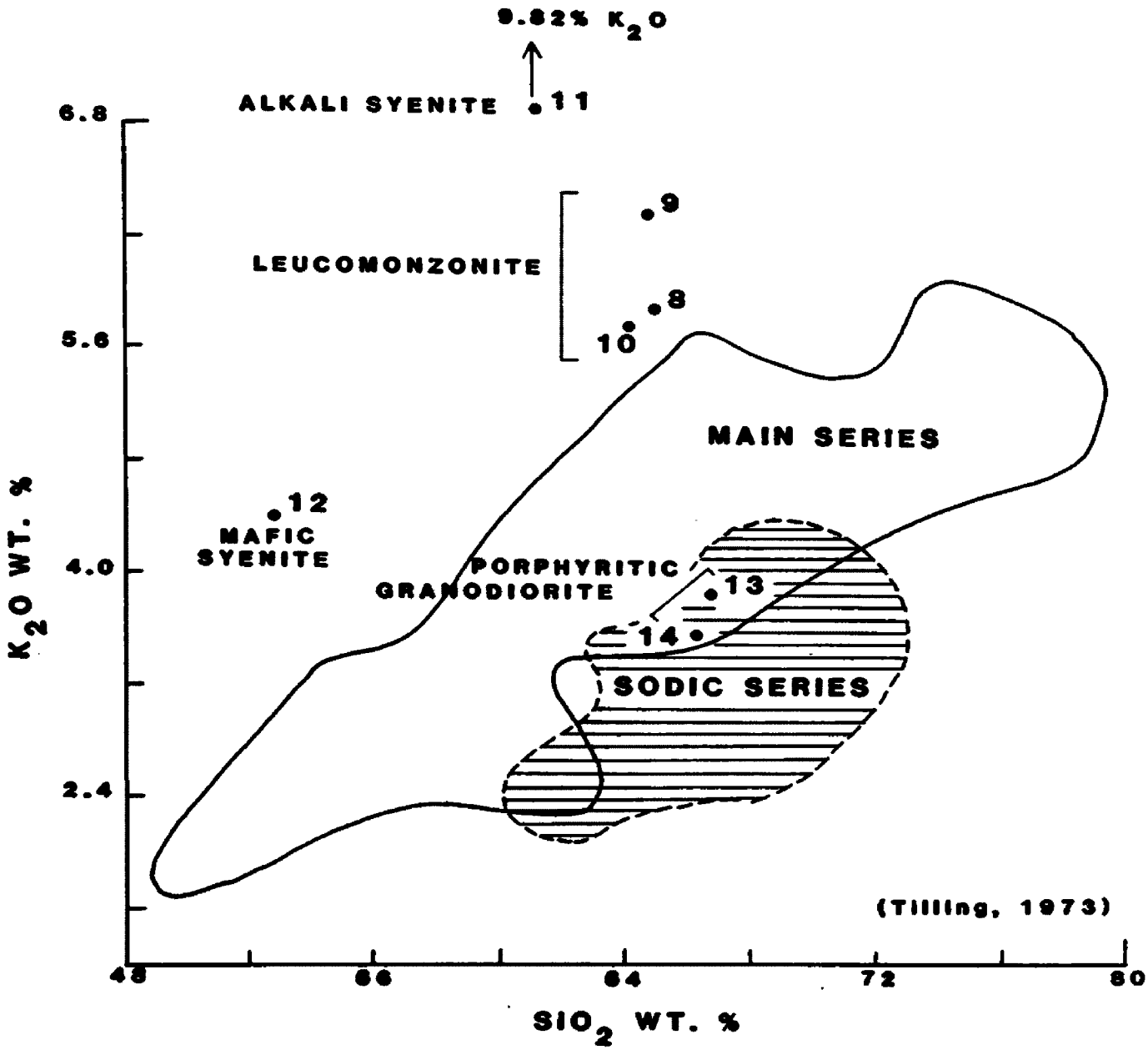
major-oxide weight-percent values and CIPW normative-mineral contents. Knopf's (1957) whole-rock chemical analyses for the leucomonzonite and porphyritic granodiorite are included for comparison. All CIPW normative-mineral contents were determined by computer using the NORM 2 program, and Fe_2O_3 and FeO values were calculated from total Fe assuming a standard Fe^{+3}/Fe^{+2} ratio of 1:1.145.

K_2O weight-percent values for the leucomonzonite, alkali-syenite, and mafic-syenite clearly show these rocks to be more potassic than the neighboring granodioritic pluton. Although these rocks occur in the northern part of the Boulder batholith, Tilling (1973) does not maintain that they are genetically related to the main magma-series. All three rock-types plot well above the main-series field on a K_2O-SiO_2 variation diagram (Figure 16). Tilling suggests that these intrusions may be related to a third, chemically-distinct magma source.

Knopf (1957) attributes the occurrence of mildly-alkalic and alkalic rock types in the tactite zone to desilication of the granodiorite by carbonate assimilation at depth. This theory holds that liquids capable of precipitating feldspathoids can form from subalkaline, quartz-rich magmas. Experimental work, however, has shown that the thermal-divide barrier in the Qtz-Ne-Ks system prohibits the development of nepheline-normative liquids from magmas saturated in silica (Wyllie, in Sørenson, 1974, p. 459). The mafic syenite, containing 2.33% normative-nepheline, is not the product of a desilicated granodiorite. The leucomonzonite is not enriched in CaO or MgO, and the relatively high CaO-content of the alkali syenite is undoubtedly due to the presence of secondary veinlets of calcium-bearing garnet from the tactite zone. It is puzzling,

TABLE 7. Whole-rock chemical analyses and CIPW normative minerals for the Priest Pass leucomonzonite, Austin alkali-syenite, Austin mafic-syenite, and porphyritic granodiorite. Location of samples shown on Figure 15. * = (Knopf, 1957)

Sample No.	8	9	*10	11	12	13	*14
Rock-Type	Monz.	Monz.	Monz.	Alkali Syen.	Mafic Syen.	Gran.	Gran.
SiO_2	64.88	64.80	64.13	61.18	52.71	66.80	66.14
TiO_2	0.55	0.57	0.52	0.59	0.97	0.39	0.43
Al_2O_3	17.62	17.53	16.77	17.47	15.97	16.45	15.69
Fe_2O_3	1.54	1.38	1.96	1.17	3.48	1.74	1.93
FeO	1.58	1.69	1.69	1.34	4.92	1.99	2.06
MnO	0.05	0.04	0.05	0.06	0.15	0.09	0.10
MgO	1.07	1.25	1.29	1.04	4.53	1.46	1.60
CaO	2.71	2.85	2.72	4.97	7.63	3.63	3.71
Na_2O	3.68	3.20	3.92	2.14	3.55	3.39	3.50
K_2O	5.89	6.59	5.87	9.82	4.41	3.85	3.54
P_2O_5	0.25	0.21	0.23	0.23	0.55	0.22	0.24
q	13.70	13.18	12.00	2.35	---	22.22	21.86
or	34.81	38.95	34.10	58.03	26.06	22.75	20.92
ab	31.14	27.08	33.17	18.11	25.73	28.69	29.62
an	11.81	12.77	11.12	9.06	14.62	16.57	16.65
ne	---	---	---	---	2.33	---	---
di	---	---	0.69	6.77	15.84	---	0.15
hy	3.83	4.01	3.60	---	---	5.38	5.57
wo	---	---	---	2.33	---	---	---
ol	---	---	---	---	6.12	---	---
mt	2.23	2.00	2.84	1.70	5.05	2.52	2.80
il	1.04	1.08	0.99	1.12	1.84	0.74	0.82
ap	0.58	0.49	0.53	0.53	1.27	0.51	0.56
c	0.86	0.45	---	---	---	---	---



K_2O-SiO_2 VARIATION DIAGRAM SHOWING MAIN AND SODIC MAGMA SERIES OF THE BOULDER BATHOLITH.

POTASSIUM-RICH ROCKS AND PORPHYRITIC GRANODIORITE SAMPLES ARE NUMBERED. THEIR LOCATIONS ARE SHOWN IN FIGURE 15. SAMPLES 10 AND 14 FROM KNOPF (1957).

FIGURE 16.

moreover, how desilication of a magma by carbonate assimilation could increase the magma's potassium content to some of the values measured here.

The most reasonable means of generating the potassium-rich rocks of the Boulder batholith is by a separate, chemically-distinct magma source. The genetic relationship between the potassium-rich rocks at the northern end of the batholith, as well as their association to the early mafic-rocks, is not clear. Modal and normative-quartz contents of the leuco-monzonite suggest that it is chemically more compatible to high-potassium calc-alkaline rocks than with rocks of the shoshonite association. The alkali- and mafic-syenites, on the other hand, appear to be more alkalic (more normative ne, less normative q) than shoshonitic counterparts with comparable SiO_2 contents. Although poor exposure obscures field relationships, the alkali- and mafic-syenites may possibly be related. It is apparent, however, that potassium-rich alkaline rocks are spatially and temporally associated with the calc-alkaline magmatism of the Boulder batholith.

CHAPTER VI

DISCUSSION

Ringing Rocks pluton is a small composite intrusion closely associated in time and space with the Boulder batholith of southwest Montana. The pluton's quartz-bearing monzonite core is chemically compatible with plutons of the main magma-series (Tilling, 1973), and appears to be about the same age as the batholith's early granodioritic intrusions. The mafic-monzonite rim constitutes the oldest, plutonic rock-type associated with the batholith, and exhibits chemical and mineralogical similarities to potassium-rich rocks of the shoshonite association. Near-contemporaneous emplacement of the two intrusions is supported by field relations and by the presence of an intervening zone of mixing. Transitional-zone rocks display a chemical composition that is intermediate between the core and mafic rim. The unique juxtaposition of the quartz-bearing monzonite core and mafic-monzonite rim of Ringing Rocks pluton appears to be structurally related, resulting from the pluton's emplacement along a major prebatholithic shear-zone.

Most of the early, batholithic mafic-rocks, and a few leucocratic varieties, are chemically more compatible to potassium-rich alkaline rocks than to the calc-alkaline trend of the Boulder batholith. Alkaline rocks are generally associated with stable, cratonic regions, or areas of tensional or neutral stress systems (Tilley, 1958). Barker (1969) notes, however, that more than 66% of known feldspathoid-bearing alkaline

occurrences in North America are closely associated with orogenic, plutonic events. The presence of mildly alkalic and alkalic igneous-rocks along the periphery of the Boulder batholith is even less surprising given their spatial proximity to similar rock-types of the central Montana alkalic province (Figure 17).

Shoshonitic volcanic rocks and/or plutonic equivalents are found in the Adel Mountains Volcanic (Lyons, 1944), Little Belt Mountains (Witkind, 1969), Highwood Mountains (Woods, 1976), and the Bearpaw Mountains (Schmidt, et al., 1961). Figure 18 compares rock compositions in terms of normative quartz, kalsilite and nepheline for the mafic-monzonite rim of Ringing Rocks pluton, a calcic melamonzonite from the Kokoruda Ranch complex (Smedes, 1966), potassium-rich rocks of the northern part of the Boulder batholith, and similar rock types from the Highwood Mountains (Woods, 1976). Alkalic occurrences associated with the Boulder batholith fall along the albite-orthoclase join with shoshonites and potassium-rich syenites from the central Montana alkalic province, suggesting a close chemical, and perhaps, genetic relationship between the two.

K-Ar age determinations on rocks from the central Montana alkalic province suggest that alkaline magmatism covered a time span of more than 20 million years, beginning in late Cretaceous time (69 m.y.) and extending into Eocene time (47 m.y.) (Daniel, et al., 1981; Marvin, et al., 1980). Shoshonitic mafic-rocks associated with the Boulder batholith predate these events by only 5 to 8 million years. Although potassium-rich alkaline rocks from the northern part of the batholith have not been dated, they are probably younger than the early mafic-varieties, and may possibly coincide with, or even postdate, some of the early alkaline rocks

of the central Montana alkalic province. In either event, it appears that a trend towards potassium-rich alkaline rocks may be extended both temporally and spatially to include the shoshonite and alkaline rock-types associated with the Boulder batholith of southwest Montana.

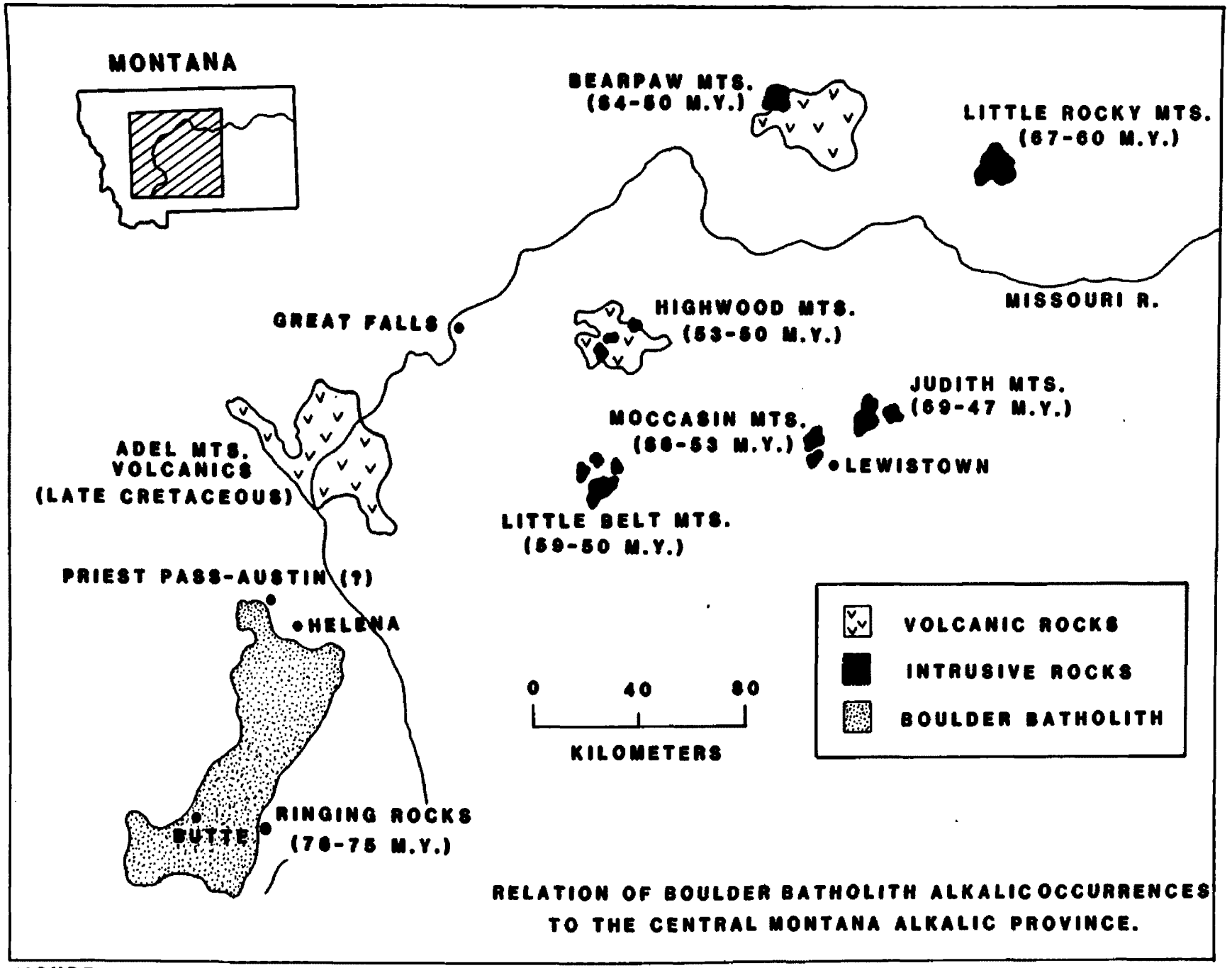
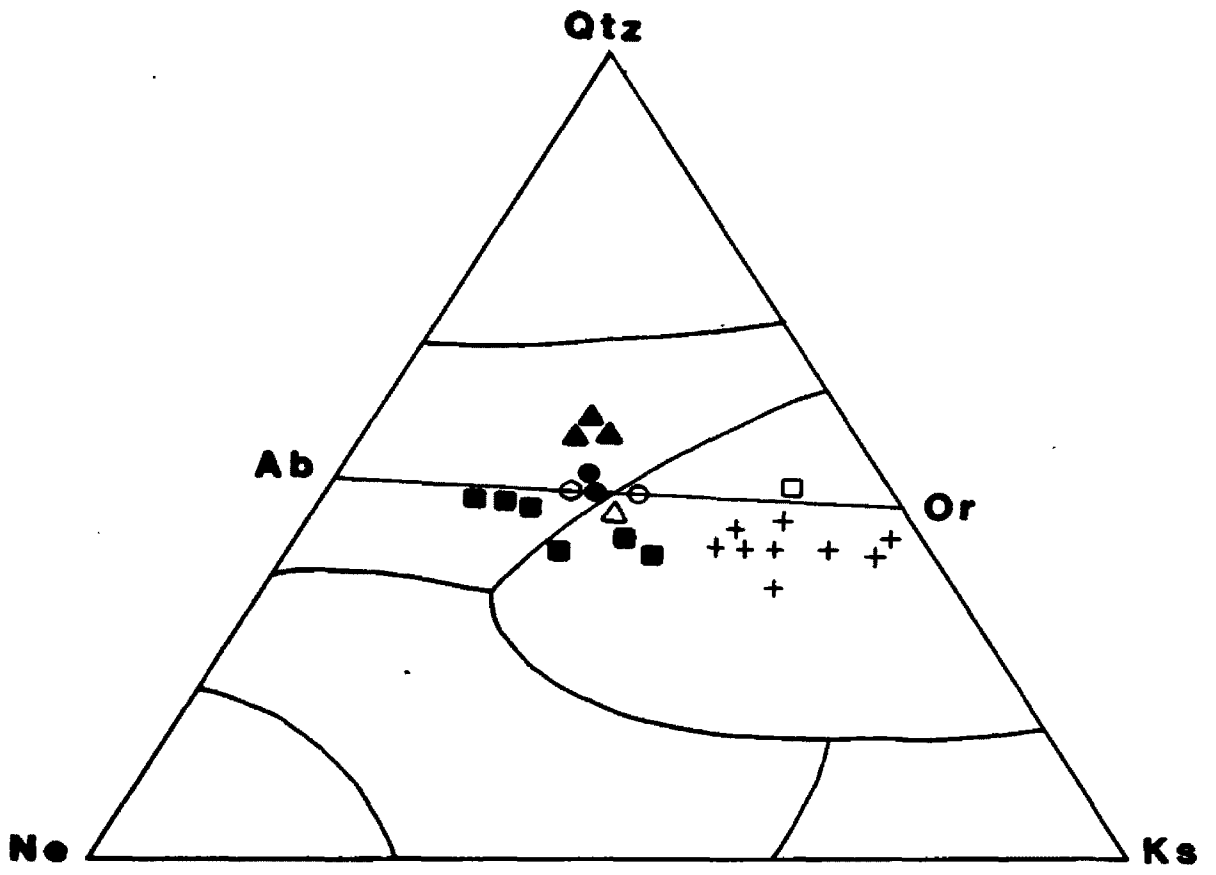


FIGURE 17.



BOULDER BATHOLITH

- ● MAFIC MONZONITE RIM
- ○ KOKORUDA RANCH
- ▲ LEUCOMONZONITE
- □ ALKALI SYENITE
- △ MAFIC SYENITE

HIGHWOOD MTS.

- ⬡ MONZONITE
- \+ SHONKINITE
- ■ SYENITE

FIGURE 18.

TERNARY Qtz-Ne-Ks SYSTEM AT P_{H2O} = 1 BAR SHOWING COMPOSITIONS OF ALKALIC ROCKS ASSOCIATED WITH THE BOULDER BATHOLITH AND HIGHWOOD MOUNTAINS VOLCANICS.

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